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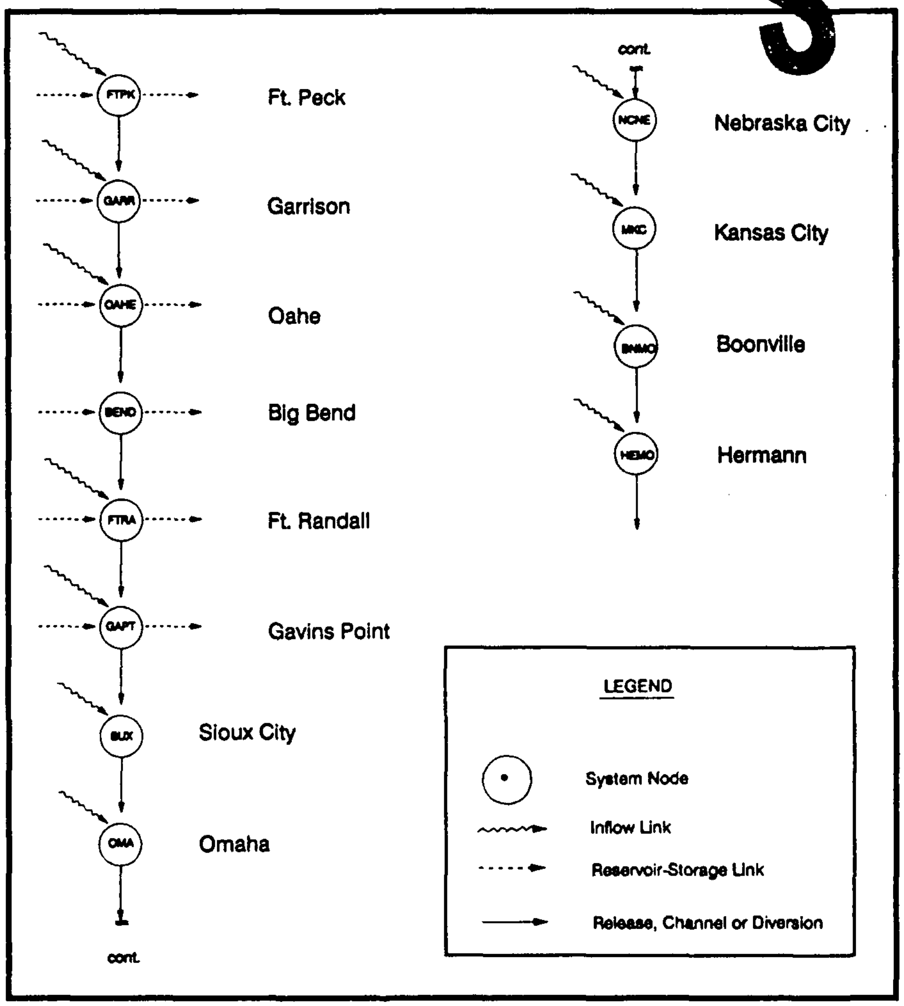
Missouri River System Analysis Model - Phase I



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PREFACE

The investigation reported herein is Phase I of a proposed two-phased project whose goal is the development of a prescriptive reservoir system operation model. The model, coined HEC-PRM, applies network-flow programming, a special case of linear programming, to reservoir system operation analysis. Phase I, begun 1 July 1990, developed and documented a trial model. Phase II, planned for 12 additional months, will expand the trial model, make technical improvements, apply the model to a system, document the application, and provide training.

The project is undertaken in accordance with a task order issued in July 1990 by MG Patrick J. Kelly, Director of Civil Works, HQUSACE. The model will be applied in the Missouri River Main Stem Master Water Control Manual Update Study. HQUSACE point of contact for the work is Earl Eiker, Chief Hydraulic and Hydraulics Branch, Engineering Division, Civil Works Directorate. The project is being jointly funded by the Missouri River Division, the National Drought Study, and the Civil Works Research and Development program.

The Project is a joint effort among the Hydrologic Engineering Center (HEC) responsible for model development and the Institute for Water Resources (IWR) responsible for economic aspects and development of the penalty functions for the Missouri River system. The IWR Phase I report is published separately. Mike Burnham, Chief Planning Analysis Division, served as project engineer. Bob Carl, Planning Analysis Division, developed the trial model and performed the test applications. David T. Ford, Engineering Consultant, provided expert advice and assistance in model formulation, development, and documentation. Darryl W. Davis, Director, provided general supervision and guidance for the project.

The Phase I report was reviewed by two individuals: Quentin W. Martin and Francis Chung. Quentin W. Martin is Manager of Water and Wastewater Utilities Program for the Lower Colorado River Authority. Francis Chung, Ph.D., P.E., who resides in Carmichael, California, is an engineer with applied experience with network-flow modeling

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SUMMARY

A prescriptive reservoir model, designated as the Hydrologic Engineering Center Prescriptive Reservoir Model or HEC-PRM, was developed and tested for use in analyzing operation of the Missouri River main-stem reservoir system. The model represents the system as a network and uses network-flow programming to allocate optimally the system water. A network approach was selected because it satisfies institutional, economic, environmental, and engineering criteria.

The network representation of the Missouri River main stem system includes six reservoir and six non-reservoir nodes. The reservoir nodes represent Ft. Peck, Garrison, Oahe, Big Bend, Ft. Randall, and Gavins Point. The non-reservoir nodes represent Sioux City, Omaha, Nebraska City, Kansas City, Boonville, and Hermann. Goals of and constraints on system operation are represented with system penalty functions.

Prior to application of HEC-PRM as a decision-support tool for the master manual update study, HEC staff devised and executed a subjective validation test, using a five-year average period. As a consequence of this test, HEC-PRM was accepted for further analyses. However, the test pointed out HEC-PRM solutions are sensitive to definition of penalty functions.

Two applications of HEC-PRM were completed: (1) analysis of the critical period for the system with the best-currently-available estimates of system penalty functions; and (2) analysis of the same critical period with a hypothetical navigation penalty function for the reach between Sioux City and Omaha.

Phase II of the Missouri River system study will (1) expand the system analyzed; (2) refine the penalty functions used; (3) improve the model's user interface; (4) make technical improvements to the model; and (5) perform selected production runs with HEC-PRM.

PROBLEM DESCRIPTION

The Missouri River main-stem reservoir system consists of six reservoirs: Ft. Peck, Garrison, Oahe, Big Bend, Ft. Randall, and Gavins Point. These reservoirs and the area they service are shown in Figure 1.

According to the reservoir regulation master manual (USACE, 1979), the main-stem system is operated "...for flood control, navigation, irrigation, power, water supply, water quality control, recreation, and fish and wildlife." Current operation priorities in operating the reservoirs to meet these objectives are described as follows in the regulation manual (pg. IX-1, IX-2):

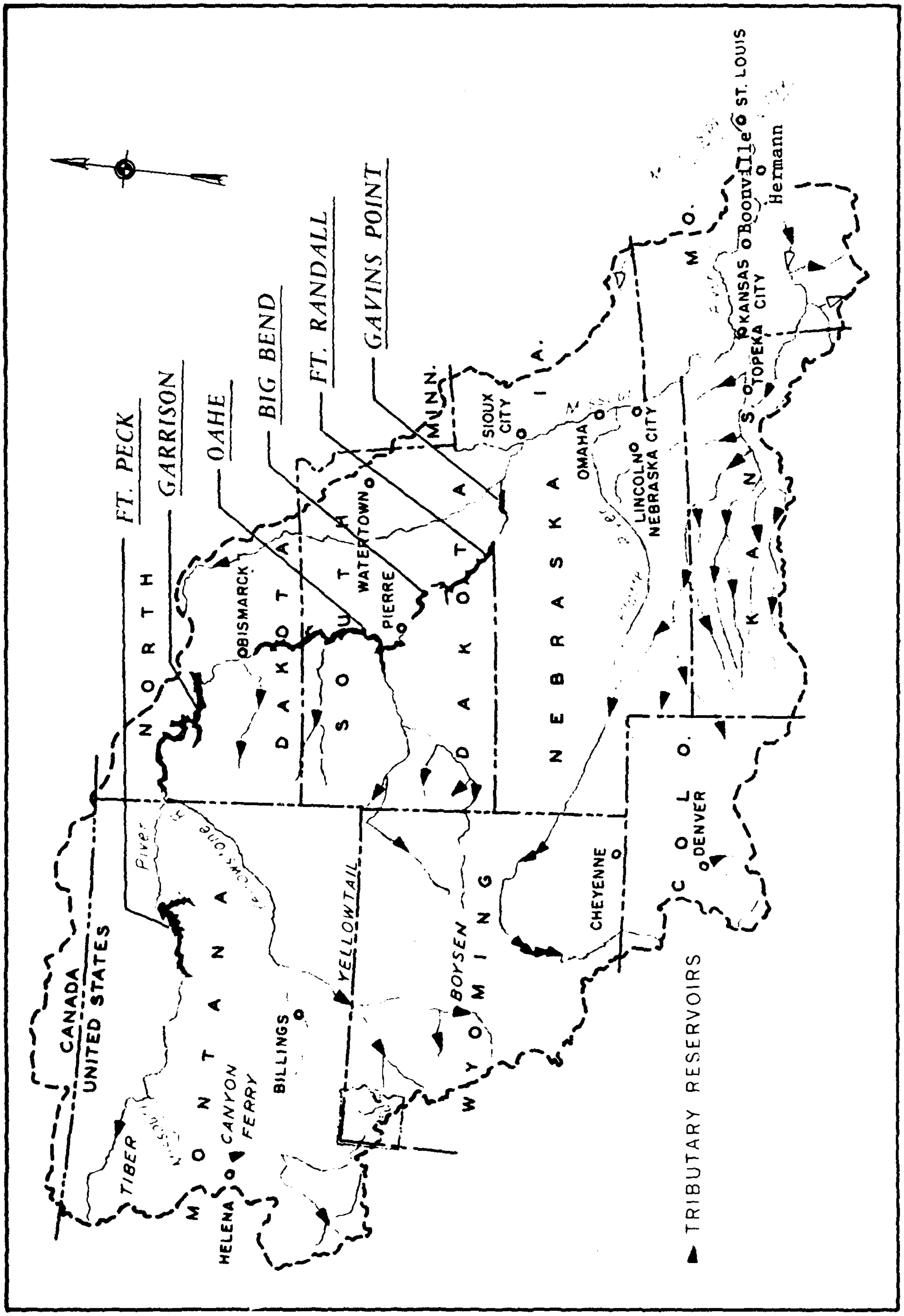


FIGURE 1 Missouri River Reservoir System

First, flood control will be provided for by observation of the requirement that an upper block of this intermediate storage space in each reservoir will be vacant at the beginning of each year's flood season...

Second, all irrigation, and other upstream water uses for beneficial consumptive purposes ... will be allowed for. This allowance also covers the effects of upstream tributary reservoir operations ...

Third, downstream M&I water supply and water quality requirements will be provided for.

Fourth, the remaining water supply available will be regulated in such a manner that the outflow from the reservoir system at Gavins Point provides for equitable service to navigation and power.

Fifth, ... the efficient generation of power to meet the area's needs ... will be provided for.

Sixth, insofar as possible without serious interference with the foregoing functions, the reservoirs will be operated for maximum benefit to recreation, fish and wildlife.

A review of these priorities was prompted by the following (USACE, 1990a):

1. It has been 10 years since the last update.

2. The current (3 year) drought has pointed out that parts of the existing Master Water Control Manual may require change...

3. Recreation on the reservoirs and the river downstream is becoming an increasingly important industry...

4. The current drought has demonstrated the importance of Missouri River water to commercial navigation...

5. The Master Water Control Manual needs to be updated to include regulation criteria for endangered and threatened species, new data collection methods, and flood history which has occurred since the last update.

ANALYSIS PROPOSED

To review the priorities in a systematic fashion, an analysis tool is required. This tool must evaluate system operation for all purposes in terms of hydrologic, economic, and environmental efficiency.

Alternative Analysis Tools

Analysis tools appropriate for the Missouri River reservoir main-stem study may be classified broadly as descriptive tools or prescriptive tools. Descriptive tools typically simulate operation with a specified operation policy. The alternative policies considered are

proposed by a user, or an alternative-generating scheme. A prescriptive tool, on the other hand, relies on a formal definition of the goals of and constraints on system operation to define best system operation. It nominates automatically the alternative policies to be considered. It evaluates the feasibility of each with a built-in simulation model. With a formal definition of operation goals and objectives, it quantifies the efficiency of each feasible alternative. Finally, after considering all alternatives, it identifies the best policy. Examples of prescriptive tools are linear-programming models, nonlinear-programming models, and dynamic-programming models.

The study procedure proposed by Missouri River Division (MRD) staff uses a descriptive tool. Staff of the MRD proposed to conduct the study in two phases. In the first,

> *... the operation of the main stem reservoir system will be simulated over the period of record from 1898 to the present to provide a base line conditions. This base line condition will be analyzed in hydrologic, economic, and environmental terms to identify issues and conflicts. Alternative water control plans ... will be formulated and evaluated in hydrologic, economic, and environmental terms. The evaluation of these alternatives will identify which of these plans favor each of the main stem project uses* (USACE, 1990a).

In the second phase, MRD staff propose to evaluate promising alternatives in further detail. The efficiency of a descriptive tool in application as proposed depends on the ability of the user, or alternative-generating scheme to nominate efficient alternatives for detailed evaluation.

HEC Proposal

After evaluating the alternative analysis tools, Hydrologic Engineering Center (HEC) staff proposed to develop and apply a prescriptive model for the Missouri River main-stem study (USACE, 1990b). The complete HEC proposal is included as Appendix A of this document.

The model proposed by HEC is a network model. Such a model represents the system operation problem with a set of nodes and arcs. A network solver finds the optimal allocation of available water to the arcs, subject to absolute limitations on that allocation. The network model demonstrates what will happen if a particular operation policy is adopted, and will indicate the policy preferred, given a set of priorities for operation. The network model is referred to herein as the Hydrologic Engineering Center Prescriptive Reservoir Model, or HEC-PRM.

HEC proposed (HEC, 1990b) to undertake the Missouri River study in two phases. In Phase I HEC promised to:

> *a. Prepare a document assessing the applicability of network-flow programming system analysis;*
>
> *b. On a trial basis, formulate and apply a network-flow model to the Missouri River main stem;*

c. Develop and document preliminary project output value functions (penalty functions) for use with the model; and

d. Present the results in a Phase I summary report.

Assessment

Appendix B of this document is HEC's assessment of applicability of network-flow programming system analysis (USACE, 1990c). HEC concluded and reported there that a network-flow programming model is appropriate for analysis of the Missouri River main-stem reservoir system because it satisfies institutional, economic, environmental, and engineering criteria.

Model Requirements

Prior to developing software to implement the proposed model, HEC staff considered the needs to be met by that model and published a software-requirements document (USACE, 1990d). The document is included as Appendix C of this report.

In summary, with HEC-PRM the reservoir-system operating problem is formulated as a minimum-cost network flow problem. All water conveyance and storage facilities are represented as arcs in the network. The volume of water allocated to the arcs depends on the cost; the objective is to minimize the total cost for the entire network.

As described in detail in Appendix D, goals of and constraints on system operation are represented with system penalty functions. The objective function of the network problem is the sum of convex, piecewise-linear approximations of these penalty functions. An off-the-shelf solver is used to define the optimal allocation of water within the system. The results of the solver are processed to report and display reservoir releases, storage volumes, channel flows, and other pertinent variables.

To the extent possible, the software is general purpose. It includes the following model-building components:

1. Inflow link;
2. Initial-storage link;
3. Diversion link;
4. Final-storage link
5. Channel-flow link;
6. Simple reservoir-release link;
7. Hydropower reservoir-release link
8. Reservoir-storage link; and
9. Node.

An analyst can specify the characteristics of and the configuration of these components to represent any system.

SYSTEM MODEL DESCRIPTION

The HEC-PRM developed for the Phase I study is a generalized computer program. Input data is entered into several files and the program is then run with no intermediate user interaction. It can be thought of as a batch execution. The heart of the program is software which solves linear equations. Built around this software is additional software which reads user input data, formats data to be consistent with the solver routines, and restructures results into comprehensible output. User input data is read from two sources: the normal ASCII (or "human readable" file) and HECDSS data files (binary files not directly readable). Penalty functions and regular interval time series data (flow and evaporation rates) are stored in HECDSS data files. The analyst enters a description of the network in the ASCII input data file in a fixed format. The description includes the time window for analysis, a list of all the nodes, a list of all the links, and information about each link. Link information includes pathname parts which form the pathname for penalty functions so the HEC-PRM may retrieve the penalty functions from HECDSS data files. It also includes connectivity and bounds information. Internally, HEC-PRM consists of several sections which perform the following:

(1) Initializes variables,
(2) Assigns pertinent disk files including ASCII input / output files and binary HECDSS data files,
(3) Reads job parameters and network description (links and nodes),
(4) Generates the solver matrix based upon the job parameters and network description,
(5) Solves the matrix to compute a least cost solution for the system, and
(6) Reformats the solver matrix and stores time series results in an output HECDSS data file.

HEC-PRM stores monthly computed flow and cost in the output HECDSS data file. The flow is stored in units of 1,000 acre-feet for each month. Separate flow and cost times series are stored for each link in the system. The analyst can modify, tabulate or graph the results using HECDSS utility programs. Manipulations include converting flow from 1,000 acre-feet per month to 1,000 cubic feet per second and computing costs for individual project purposes (e.g. recreations, flood control, etc.) using the original component penalty functions.

The network representation of the Missouri River main stem system includes six reservoir and six non-reservoir nodes, as shown by Figure 2. The reservoir nodes represent Ft. Peck, Garrison, Oahe, Big Bend, Ft. Randall, and Gavins Point. The non-reservoir nodes represent Sioux City, Omaha, Nebraska City, Kansas City, Boonville, and Hermann.

An inflow link terminates each period at the Ft. Peck, Garrison, Oahe, Ft. Randall, and Gavins Point reservoir nodes. There is no local inflow into Big Bend Reservoir and therefore there is no inflow link to that node. An inflow link terminates each period at all non-reservoir nodes. An initial-storage link terminates at each reservoir node in the first period of analysis. The network ends with a diversion link at Hermann each period. A final storage link originates at each reservoir node in the final period of analysis. Channel-flow links connect the six non-reservoir nodes each period. A reservoir-release link connects each reservoir node with the next downstream node each period. Storage in each reservoir each period is represented with a reservoir-storage link.

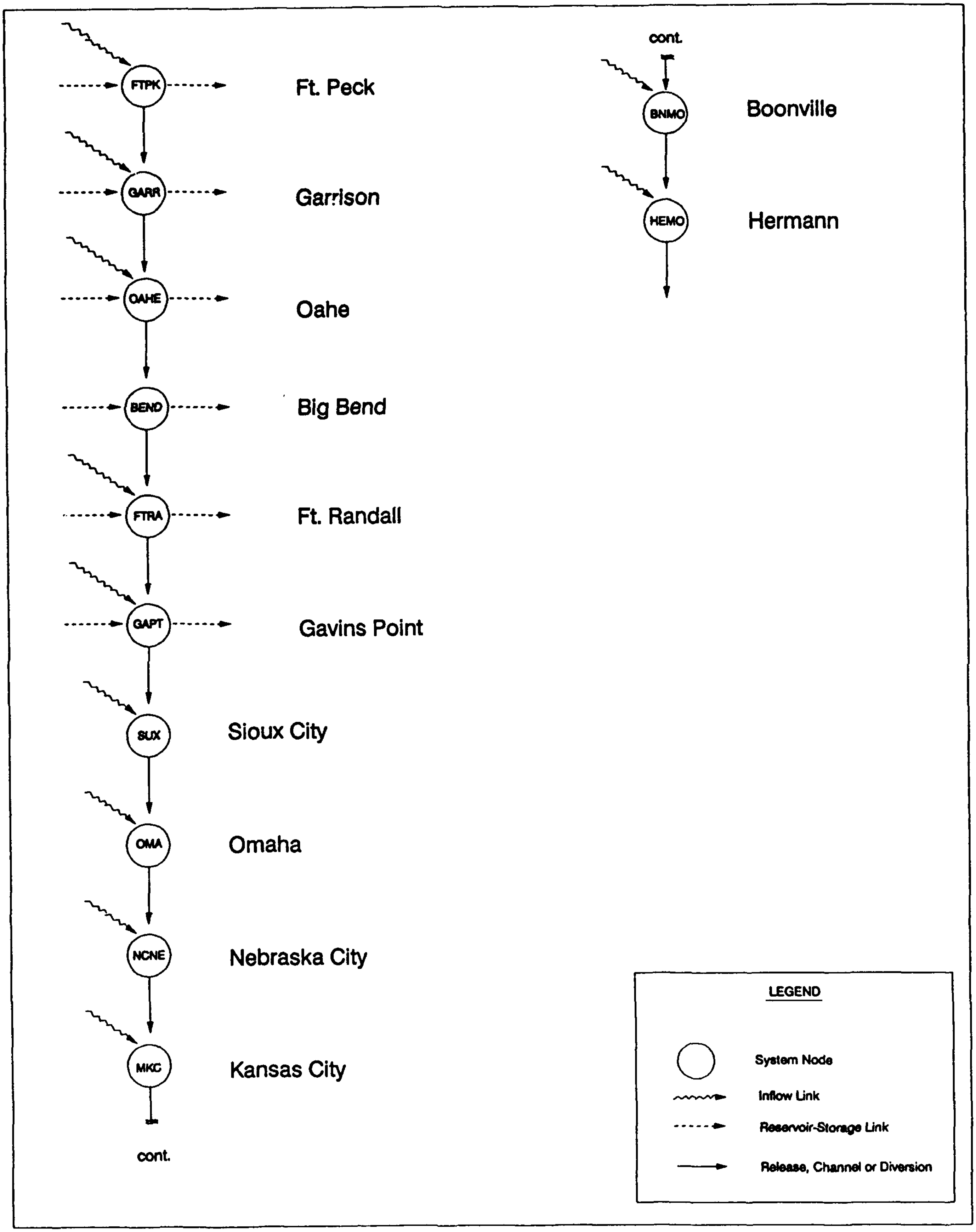


FIGURE 2 Single-period Link-node Representation of Missouri River System

Additional details of the network representation of the Missouri River reservoir system are presented in Appendix D. This appendix is a reproduction of HEC's description of the Missouri River system model (USACE, 1990e).

PENALTY FUNCTIONS

Goals of and constraints on Missouri River reservoir system operation are represented with system penalty functions. For the Phase I study, functions were developed by the Institute for Water Resources (IWR). Procedures for developing these functions are presented in a separate document (USACE, 1990f).

Penalty functions are of two types: cost-based or non-cost-based. The cost-based functions, "...show the loss in economic value as the flow in each model link deviates from the optimum flow (USACE, 1990f)." In this application, individual economic cost-based penalty functions were developed for the following outputs: urban and agricultural flooding; water supply; recreation; hydropower; and navigation. These functions vary by month if appropriate.

Non-cost-based penalty functions represent goals of system operation that cannot be quantified in economic terms. For example, a flow requirement for fish and wildlife protections may be represented with a penalty function in which the penalty arbitrarily is set to force the desired operation. In this case, "... the aggregate optimum system penalty cannot be interpreted in purely economic terms, and the cost-based and non-cost-based penalties need to be reported separately (USACE, 1990f)."

For analysis of system operation, the individual purpose penalty functions for each system location are summed. The resulting functions are represented in a piecewise-linear fashion for HEC-PRM. The piecewise-linear convex functions used in this study are included as Appendix E of this document.

MODEL VALIDATION

Unlike a descriptive model, a prescriptive model cannot be validated directly by comparison with an observed data set. No such data set can exist because historical operation is never truly optimal for the objective function used in the model, and the objective function used in the model never reflects exactly all goals of and constraints on operation.

Model logic, input data, and solution algorithms can be scrutinized. HEC staff did so. In addition, HEC staff explored model validity by applying HEC-PRM to analysis of a meaningful period, comparing the results to operation with current rules, and assessing critically the differences. If the HEC-PRM results were judged reasonable for this test application, the model would be accepted as a tool for subsequent analyses.

Validation Procedure

MRD system operation was analyzed with HEC-PRM for a five-year average flow period, March 1965 to March 1970. This period was recommended by MRD staff as one which includes no extreme high-flow or low-flow events. Hydrologic data for the period were provided by MRD; these data include monthly reservoir inflows and local flows, depletions, and lake evaporation rates. Initial and final storage values for the main-stem reservoirs are identical to those used with the MRD reservoir simulation model applied to the same period.

Composite, piecewise-linear penalty functions were developed for all purposes at all locations and were provided by IWR. Only economic (cost based) penalty functions are used. For this validation, the nonlinear hydropower penalty functions were approximated as a linear function of reservoir release only by assuming a fixed head. Maximum reservoir storage was limited to the top of annual flood-control and multiple-use zone. Minimum storage was limited to the top of permanent pool.

To test the reasonableness of the results, HEC staff compared HEC-PRM results with those of the MRD reservoir simulation model. This comparison is intended only to identify obvious shortcomings of HEC-PRM, inexplicable results, or weaknesses that would render HEC-PRM unacceptable for further analyses. A perfect match of results was not expected. Indeed, the results should not be identical, as the models employ different simplifications of the real system and operate for different goals. The MRD model follows existing operation rules, and HEC-PRM operates to minimize total system penalty for the period. Furthermore, with a linear model, alternative optimal solutions may exist. That is, alternative allocations of flow to the network arcs may yield the same total penalty. The network solver will find only one of these solutions.

Results

Computed time-series reservoir storages values for Ft. Peck, Garrison, Oahe, and Ft. Randall are shown on Figure 3. Storages indicated by HEC-PRM are shown in green, and those indicated by the MRD model are shown in red. This same color scheme is used for all figures depicting the validation results. Figure 3 also shows the current allocation of reservoir capacity to the permanent pool, carry-over and multiple use, annual flood-control and multiple use, and exclusive flood control zones. Proposed releases from Ft. Peck, Garrison, Oahe, and Ft. Randall are shown on Figure 4. Downstream flows at Kansas City, Nebraska City, Kansas City, and Boonville are shown on Figure 5. All storage is shown in 1,000 acre-feet (KAF). All flow is shown in 1,000 acre-feet per month (KAF/MON). To convert flow from KAF/MON to 1,000 cubic feet per second (KCFS) multiply by .01653. To convert flow in KCFS to KAF, multiply by 60.5. The conversions assume 30.5 days/month.

The pattern of storage indicated by the two models for Ft. Peck on Figure 3 matches well. The seasonal cycles are identical. HEC-PRM proposes slightly less storage for 1967-1969. Some slight differences in the storages are attributable to HEC-PRM's approximation of the evaporation. At lower storages, the evaporation is overestimated. This is true for all reservoirs. Reservoir releases proposed by the two models on Figure 4 shows that the major difference in storage for 1967-1969 is a consequence of greater releases proposed by HEC-PRM for that period. These releases are constant at 847 KAF.

Inspection of the penalty functions for Ft. Peck release (Figure E-7, Appendix E) and Ft. Peck storage (Figure E-1, Appendix E) reveals why this value is critical. The reservoir release arcs are defined by two links located in series below each reservoir: (1) energy release link and (2) all other release purposes link. The Ft. Peck energy release link is defined by two arcs (Figure E-7). The unit penalty (or slope of the penalty function) for the first arc (release between 0 and 847 KAF/MON) is -2.48 thousand dollars/KAF computed as follows:

$$\text{unit penalty} = \frac{(P_2-P_1)}{(R_2-R_1)} = \frac{(1.091-3.191)}{(847-0)} \approx -2.48$$

where:

P_1, P_2 is penalty in thousands of dollar
R_1, R_2 is reservoir release in KAF/MON

The unit penalty for the second arc is zero (no change in cost for releases greater than 847 KAF/MON). Similarly, the Ft. Peck storage link is defined by 4 arcs (Figure E-1). As an example, the unit penalty (or slopes of the penalty function) for July is computed as shown on Table 1.

TABLE 1
Ft. Peck July Penalty Function

Arc	Storage (KAF)	Penalty ($1,000)	Unit Penalty
-	0	4.2	-
1	11,070	.627	-.323
2	14,900	.108	-.136
3	16,550	.137	+.0176
4	18,550	.539	+.201

If HEC-PRM must only decide between storing or releasing water from Ft. Peck and if there is sufficient water, then it will always release 847 KAF/MON because that arc has the least unit cost (-2.48). It will then try to store water until the reservoir contains 14,900 KAF. It will avoid storing water above that because the storage arcs 3 & 4 have unit costs (+.0176 and +.201) greater than that for energy release arc 2 (zero). HEC-PRM cannot always release that amount because there is either a shortage of water or there are other higher priority needs at other links in the network.

The Ft. Peck release proposed by HEC-PRM falls to zero in several months. This seems odd, but is not totally unexpected. Two complicating factors play a role in release selection with HEC-PRM. First, the solver finds a minimum-cost flow allocation by setting iteratively a set of releases, storages, and flows at their upper or lower bounds. Second, HEC-PRM looks ahead in time and downstream in space when making release decisions.

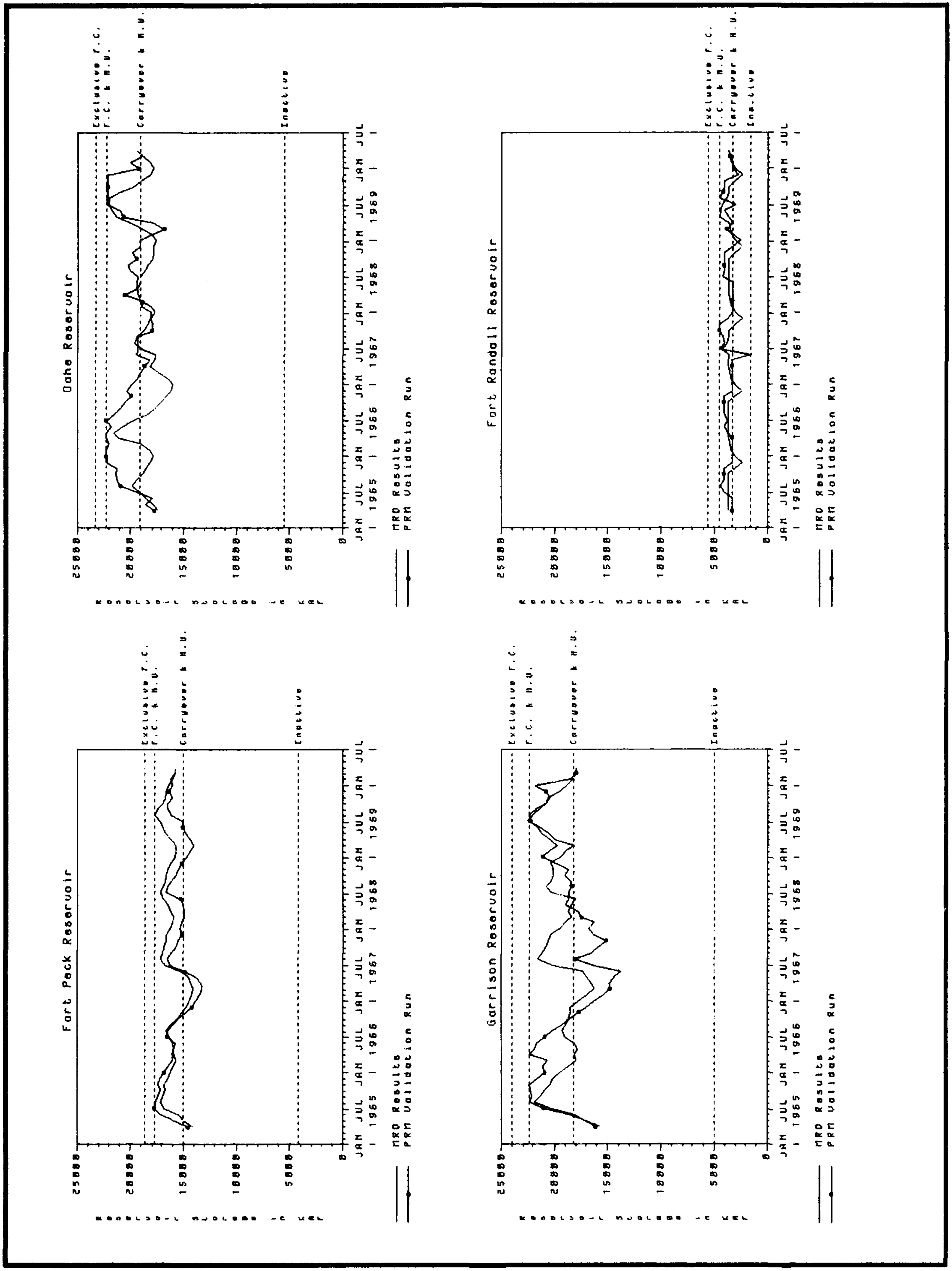


FIGURE 3 Reservoir Storages for Validation Analysis

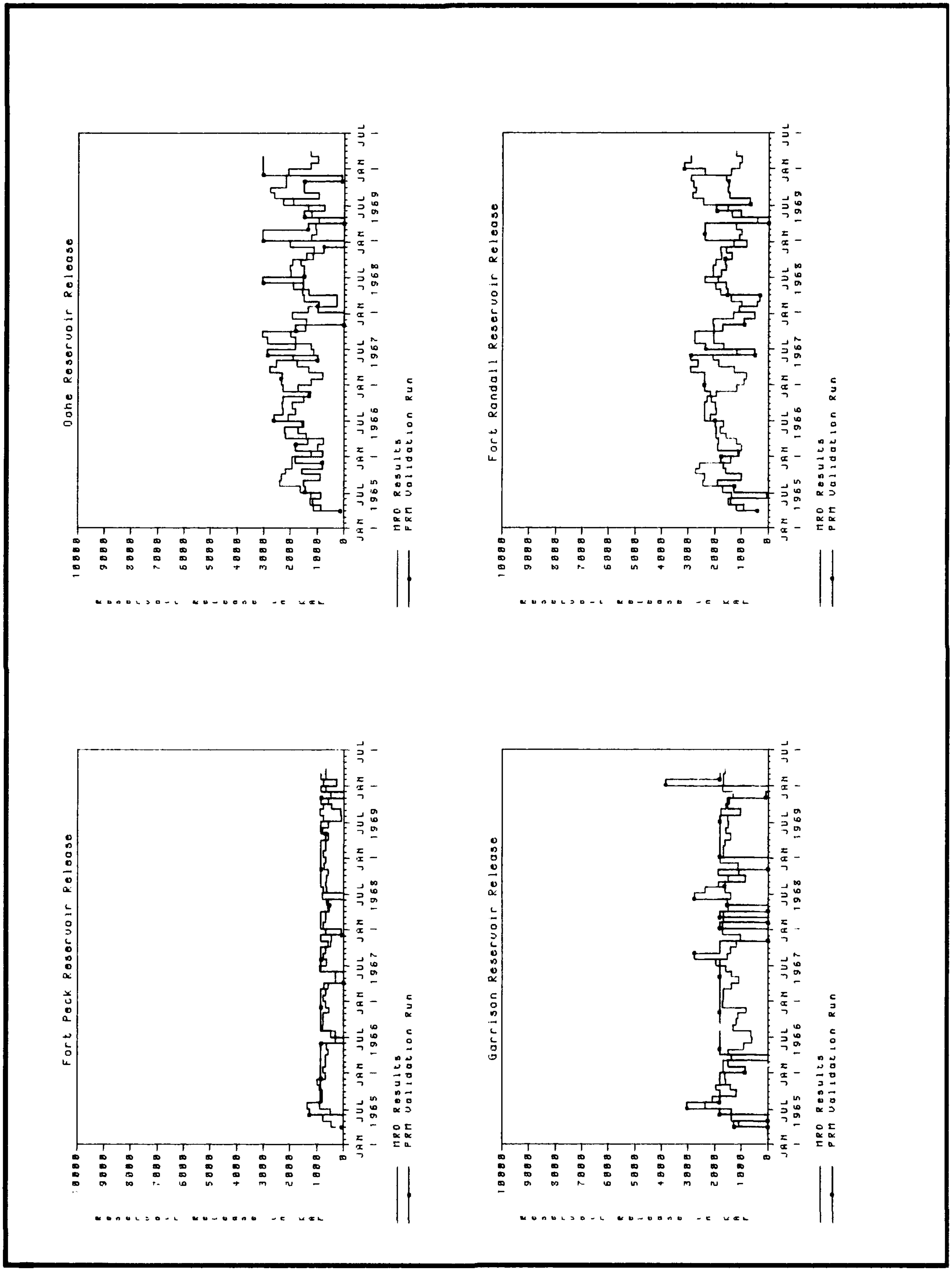


FIGURE 4 Reservoir Releases for Validation Analysis

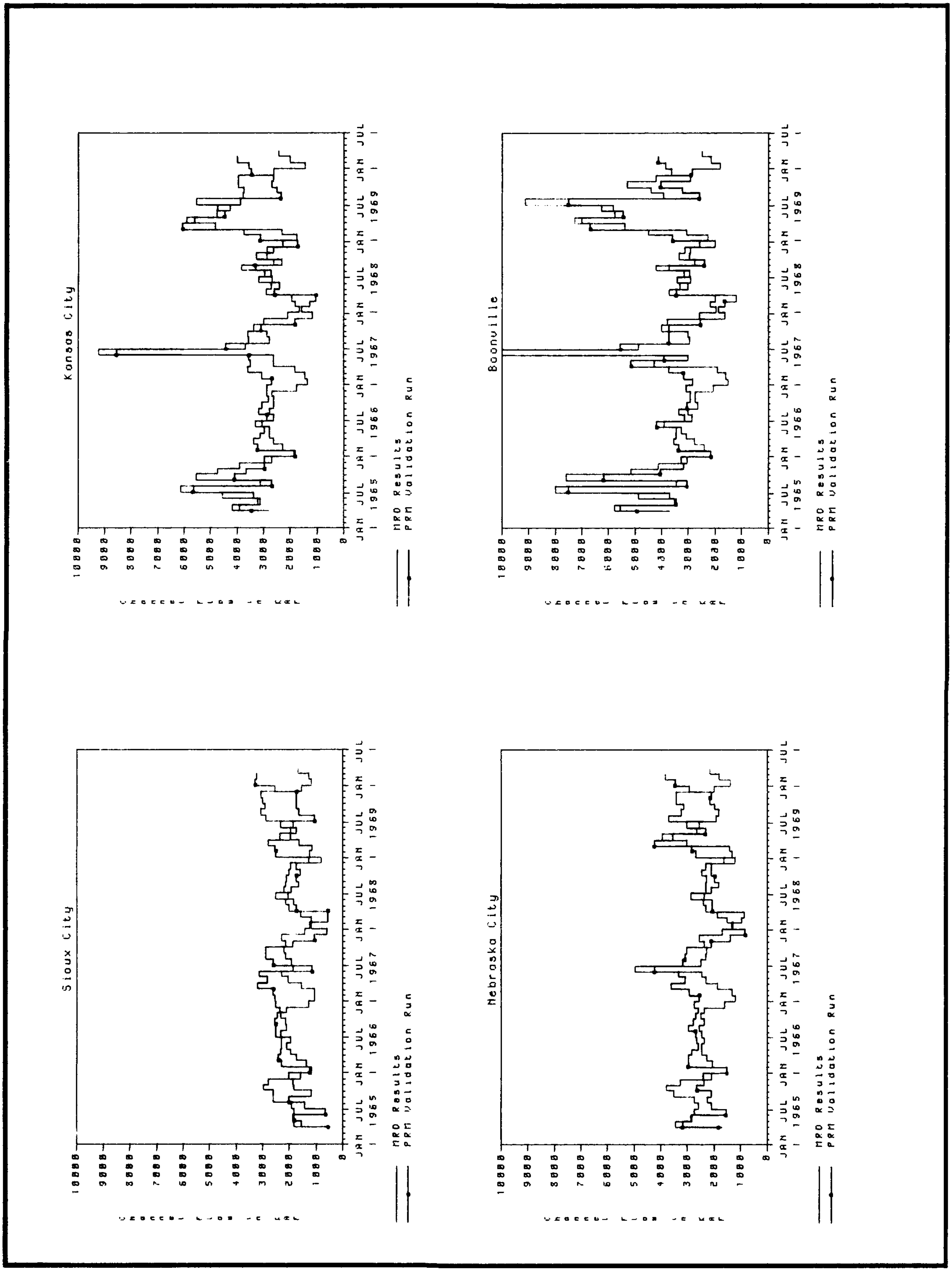


FIGURE 5 Downstream Flows for Validation Analysis

The first complication is illustrated with a simple one-month reservoir-operation problem. In this problem, the initial storage is 3 KAF, and the net inflow is 7 KAF. The reservoir capacity is 10 KAF and the outlet capacity is 10 KAF. The governing equation is the continuity equation:

$$S_f + R = S_i + I \qquad (1)$$

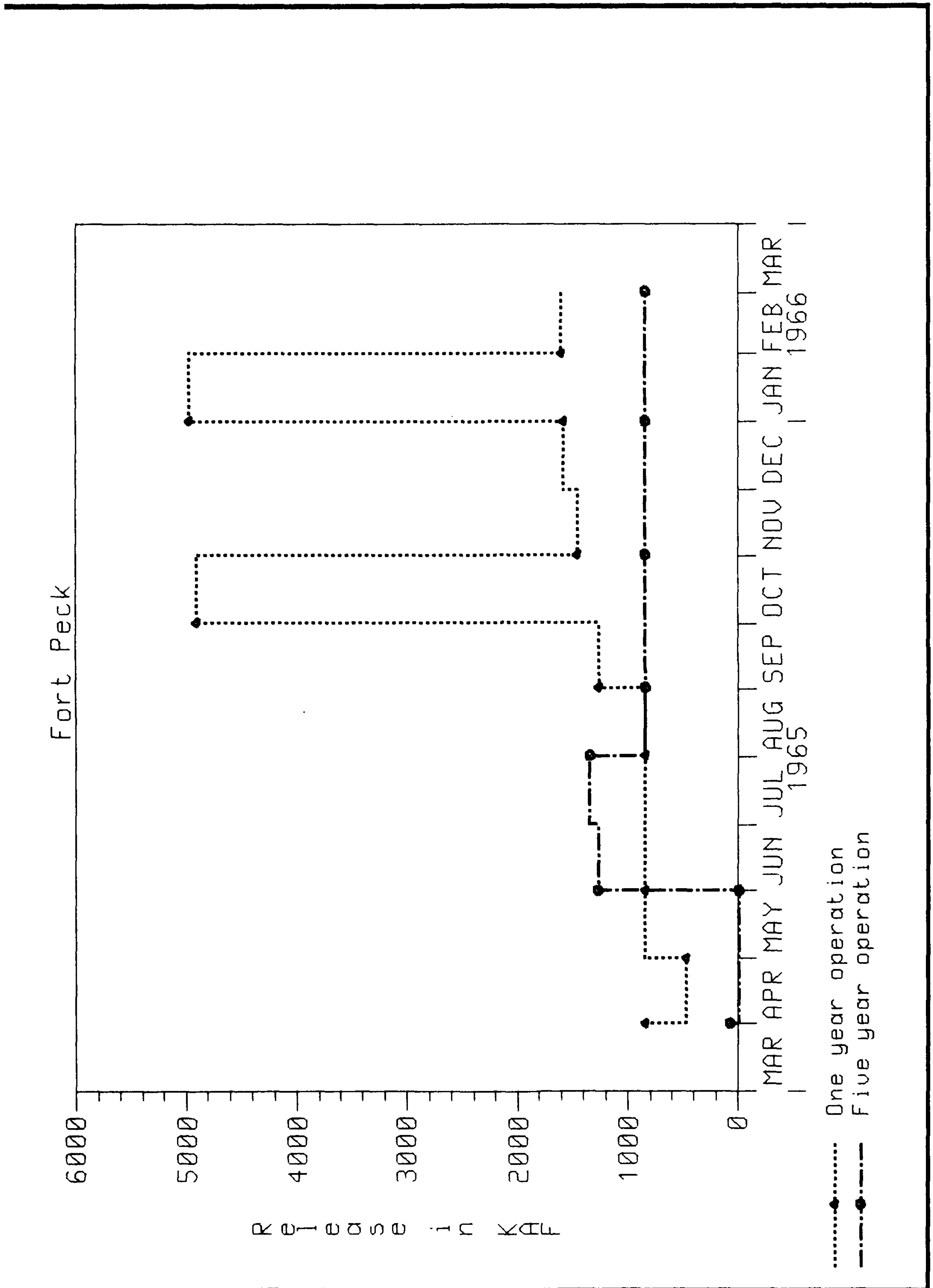
in which:

S_i = the initial storage;
I = inflow volume;
R = release volume; and
S_f = final storage.

This equation is written so the variables representing decisions are on the left-hand side and the known quantities are on the right-hand side. Suppose that the unit penalty on storage is \$1000/KAF, and the unit penalty on release is \$1000/KAF. What is the minimum-cost operation? The answer is that no unique optimal solution exists. Any combination of release and final storage which totals 10 KAF is feasible (satisfies the continuity equation). Furthermore, any feasible combination will have exactly the same total penalty. The network solver (or any linear program solver) will pick an extreme-point solution: a solution in which at least one of the decision variables is at its upper or lower bound. In the example, it will select either R = 0 KAF and S_f = 10 KAF or R = 10 KAF and S_f = 0 KAF. In practice, a knowledgeable reservoir operator might select other values of R or S_f for reasons that are not represented by the model objective function. For example, the release selected might be approximately the previous-month's release. However, if this operation criterion is not represented explicitly by the cost-based or non-cost-based penalty functions, HEC-PRM will not consider it in selecting releases.

In the Ft. Peck case, the lower bound on release is zero, so the solver found one minimum-cost solution with the release set to zero. Intuition suggests that another solution may exist with the release set to 847 KAF, the optimum value for hydropower. To examine this further, HEC-PRM was run with the minimum release for Ft. Peck increased to 847 KAF. In that case, the model was not able to find a feasible solution for the 5-year analysis, given the feasible range of storage at Ft. Peck.

The second complicating factor in understanding easily a release selected by HEC-PRM is that HEC-PRM looks ahead in time and downstream in space when selecting that release. Consequently, a release that seems optimal on examination of short-term operation may, in fact, be suboptimal for the long-term. To illustrate this, HEC-PRM was run for only the first year of the five-year validation period. In that case, operation of Ft. Peck for future inflows and demands was not a consideration. The Ft. Peck releases for the one-year operation are shown on Figure 6. The proposed releases for the first year of the five-year period are shown on the same figure. In the one-year period, HEC-PRM proposed releases to reduce the hydropower penalty. With this short-sighted operation, the future value of water is ignored. On the other hand, the releases proposed for the first of five years result in holding water in storage for subsequent delivery.



GURE 6 One-year Validation Analysis

The storages for Garrison, again, shown on Figure 3, matches the general pattern well. The storage indicated by HEC-PRM from mid-1966 to early 1968 is about 20% less than that indicated by the MRD model. In that same period, HEC-PRM has proposed greater release, as shown by Figure 4. As with Ft. Peck, this is due to the energy penalty function: The advantage of releasing water for energy exceeds the advantage of storing it in these months, even for future use. Thus HEC-PRM draws down the reservoir. HEC-PRM calls for no release from Garrison several months in the validation period. No minimum release is mandated, and the value of water in storage exceeds the value of water released. The efficiency of this decision is clearer when the downstream flows are inspected.

The overall Oahe storage pattern, shown on Figure 3, follows the pattern of the MRD model. Inspection of Figure 4 reveals that the releases proposed by HEC-PRM again tend to be at extremes: They fluctuate from zero to approximately 3000 KAF. This is due, in part, to the energy penalty function. The penalty drops to zero at approximately 3000 KAF. Consequently, greater releases will not reduce the total system penalty.

Ft. Randall storages proposed by the two models are shown on Figure 3. These match well, with what appears to be a slight time lag in the HEC-PRM results. This time lag may be the result of the capability of HEC-PRM to incorporate knowledge of future inflows in making release decisions: If postponing releases will reduce the overall penalty, HEC-PRM will do so. Figure 4 shows the releases proposed by the models. In one of the 60 months, the release falls to zero.

Figure 5 reveals much about the upstream reservoir releases. This is plots of the flow at Sioux City, Nebraska City, Kansas City, and Boonville. The Kansas City flow penalty function is presented on Figure E-16 of Appendix E. The unit penalty is very high for flow less than approximately 500 KAF. The unit penalty is less between 500 and 2300 KAF. The unit penalty is zero between 2300 KAF and 3600 KAF, increases rapidly as flow increases to about 12300 KAF, and is greater still for flow in excess of 12300 KAF. Local inflow downstream of Gavins Point often exceeds 500 KAF, so no releases are necessary to avoid the penalty for low flow. In June 1967, the local inflow between Gavins Point and Kansas City was 7735 KAF. HEC-PRM, in analyzing all periods simultaneously, was able to foresee the downstream impact of releases during this period. Consequently, the releases were limited, and in some cases reduced to zero, to avoid a very high penalty at Kansas City and downstream.

Conclusion

As a consequence of the validation test, HEC-PRM is accepted for subsequent analyses. It is clear from the test results that the model does what it is supposed to do: It defines a minimum-penalty allocation of system water. However, the test reveals the sensitivity of the model to the penalty functions used. HEC-PRM will store water if the penalty functions are defined in such a manner that releases of zero do not incur penalties that exceed those for storing water instead.

MODEL APPLICATION

Two applications of HEC-PRM were completed: (1) analysis of the critical period for the system with the best-currently-available estimates of system penalty functions; and (2) analysis of the same critical period with a hypothetical navigation penalty function for Sioux City flow. The reservoir storage levels, reservoir releases, and downstream flows are shown on Figures 7, 8, and 9, respectively. The results of the analysis of the critical period for the system with the best-currently-available estimates of the system penalty functions are shown in red for all plots. The results of the analysis with inclusion of the hypothetical navigation penalty function is shown in green for all plots.

Critical Period With Best-currently-available Penalty Functions

The critical period for the system was identified by MRD staff as March 1930 - March 1949. This includes the 12 year (1930 - 1941) drought of record and the period required for refilling of reservoirs when following current operation policy. Hydrologic data for the critical period were provided by MRD. These data include reservoir inflows and local flows, depletions, and lake evaporation rates.

Penalty Functions and Operation Constraints. Composite, piecewise-linear penalty functions were developed for all purposes at all locations for which penalty functions were provided by IWR. Only economic (cost-based) penalty functions are used. Hydropower penalty functions were linearized by assuming a fixed head for the entire period. Maximum reservoir storage was limited to the top of the annual flood-control and multiple-use zone. Minimum storage was limited to the top of permanent pool.

Results. As a rule, energy generation dominates the operation. HEC-PRM proposes release of water to drive the energy penalty to zero if sufficient water is available. Otherwise, it proposes making no release and storing water for subsequent use. This is again a case of long-term verses short-term operation decision making. The model must choose between making minimum releases for hydropower now or storing water for later use. It chooses the latter based on total system penalty, as defined by the penalty functions. Although a skilled operator might choose a less drastic operation, the penalty functions used in this application do not indicate that another policy is better, although it may be as good.

Figure 9 shows channel flows at Sioux City, Nebraska City, Kansas City, and Boonville if the system is operated according to the policy found by HEC-PRM. At Sioux City, the penalty would be great if the flow is less than approximately 500 KAF in January or less than 1600 KAF in the remainder of the year. HEC-PRM has proposed releases that will meet this minimum. At Kansas City, the penalty would be great if the flow is less than 500 KAF in January or 2200 KAF in the remainder of the year. Again, HEC-PRM has proposed releases to meet this minimum. Similarly, HEC-PRM has proposed releases that will limit the channel flow at Sioux City to well below the discharge at which penalty again is great. This is 2500 KAF in January or 8000 KAF in the remainder of the year. In fact, most flows are in the range between the desired minimum and the desired maximum, thereby incurring little or no penalty. The same is true at Kansas City. The flow is frequently in the range 500 or 2200 KAF to 3600 KAF. The flow at Kansas City is clearly outside this range in 1947 and again in 1951. However, reservoir operation could do little to reduce these extreme flows, as they are the consequence of uncontrollable local inflow. For example, when the Kansas City flow reaches approximately 10000 KAF in 1951, the local inflow between Nebraska City and Kansas City is almost 9000 KAF.

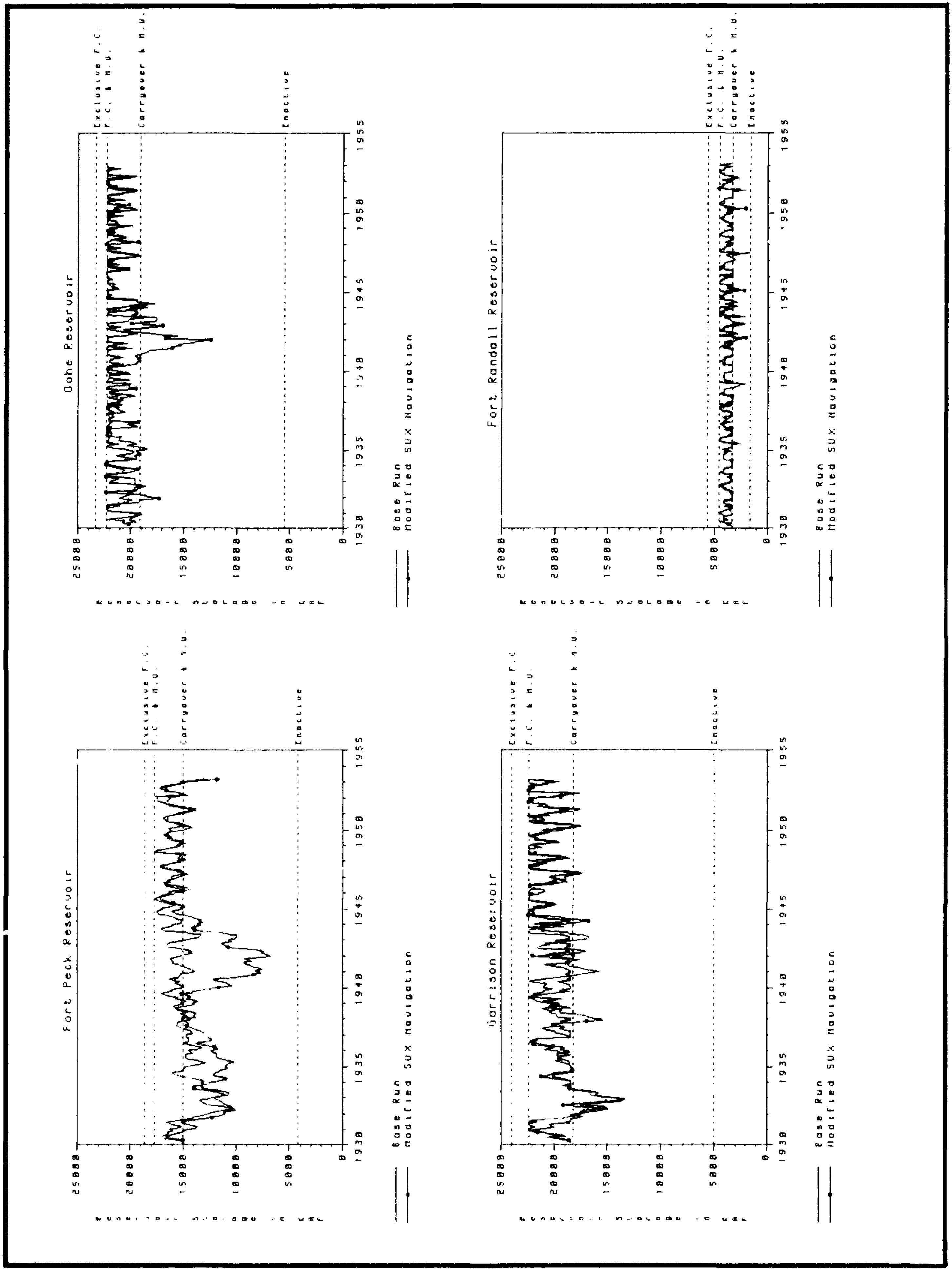


FIGURE 7 Reservoir Storages for Critical Period Analysis

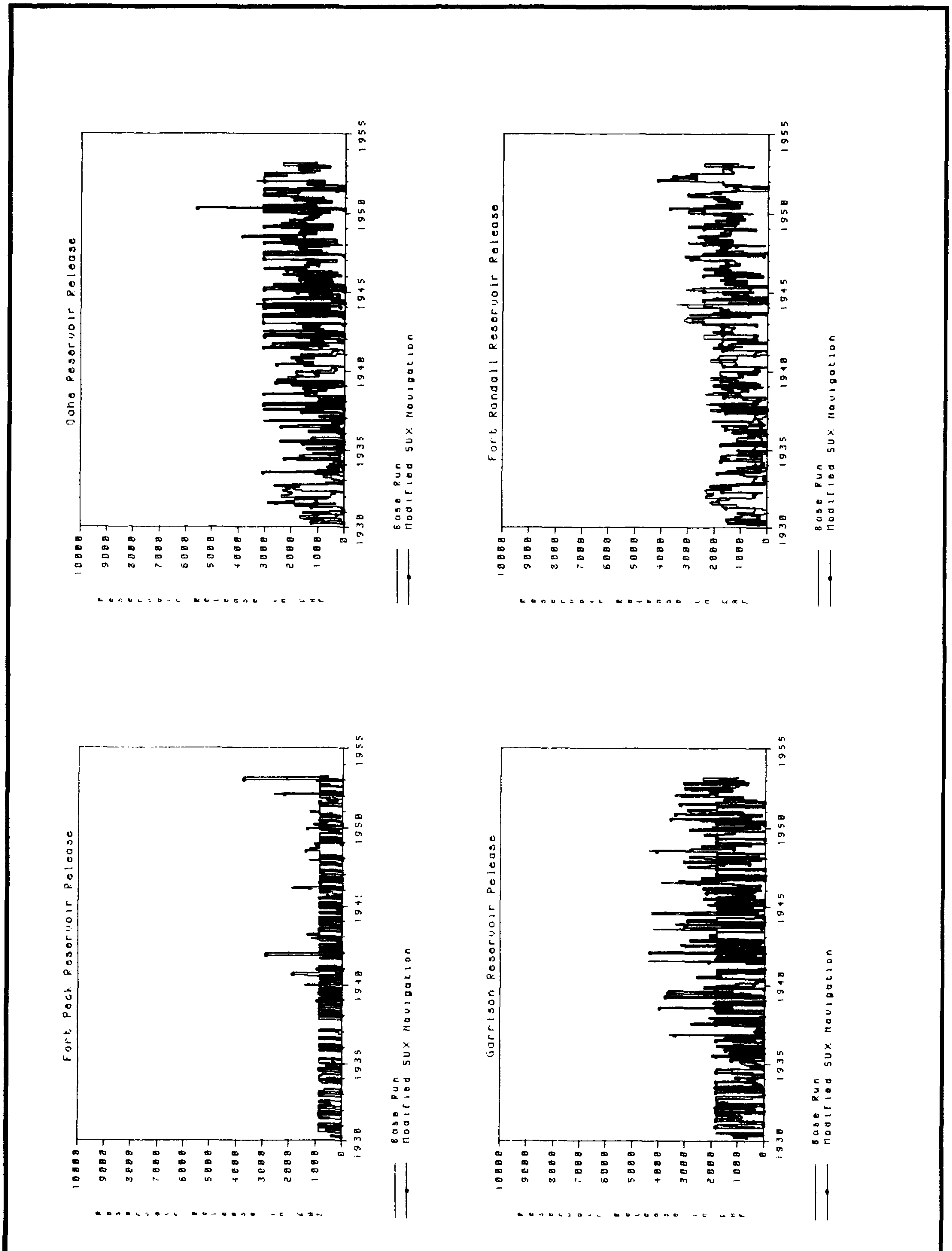


FIGURE 8 Reservoir Releases for Critical Period Analysis

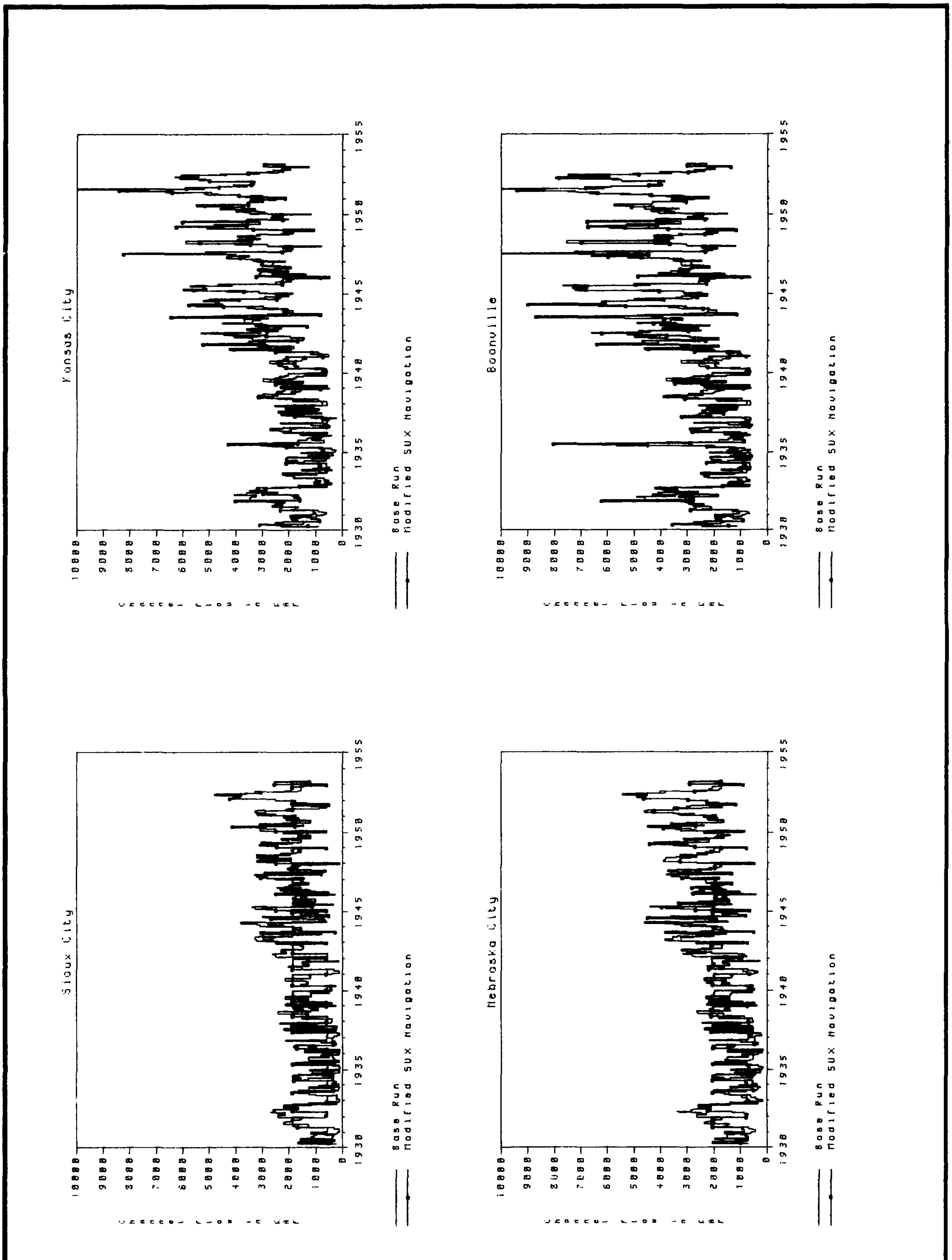


FIGURE 9 Downstream Flows for Critical Period Analysis

Critical Period With Hypothetical Navigation Penalty Function For Sioux City.

In the second application of HEC-PRM, operation was analyzed for the same period described in the previous section. A hypothetical navigation penalty function was added to demonstrate the impact of system operation for high-penalty downstream requirements.

Penalty Functions and Operation Constraints. As in the previous application, composite, piecewise-linear penalty functions were developed for all purposes at all locations for which penalty functions were provided by IWR. However, for the reach between Sioux City and Omaha for April-November, the function was replaced with the hypothetical navigation penalty function shown on Table 2.

TABLE 2
Hypothetical Navigation Penalty Function for Sioux City

Flow range, in KAF (1)	Penalty, in $1000/KAF (2)
0 - 1875	10.7
1875 - 7200	0
7200 - 13900	0.149
13900 - 21000	2.67

Figure 10 depicts the June navigation penalty functions for Sioux City. Included are the best currently available navigation function and the edited hypothetical navigation penalty function.

Hydropower penalty functions were linearized by assuming a fixed head for the entire period. Maximum reservoir storage was limited to the top of the annual flood-control and multiple-use zone. Minimum storage was limited to the top of permanent pool.

Results. The hypothetical navigation penalty function causes the flow pattern at Sioux City to be smoother, as the range of flows there is reduced. Often the system has operated to provide exactly 1875 KAF during April-November. For December-March, the system has reduced releases to a bare minimum to conserve water to meet subsequent April-November demands. Even so, to satisfy the 1875 KAF minimum at Sioux City, the system must draw down Ft. Peck, Garrison, and Oahe, starting in 1939. For example, the January 1942 storage at Ft. Peck falls to 7000 KAF, whereas without the hypothetical function, it was approximately 15000 KAF. Earlier and later in the critical period, the Ft. Peck storages are approximately the same with and without the function. Then sufficient water is available to meet the demand without drawing on upstream storage.

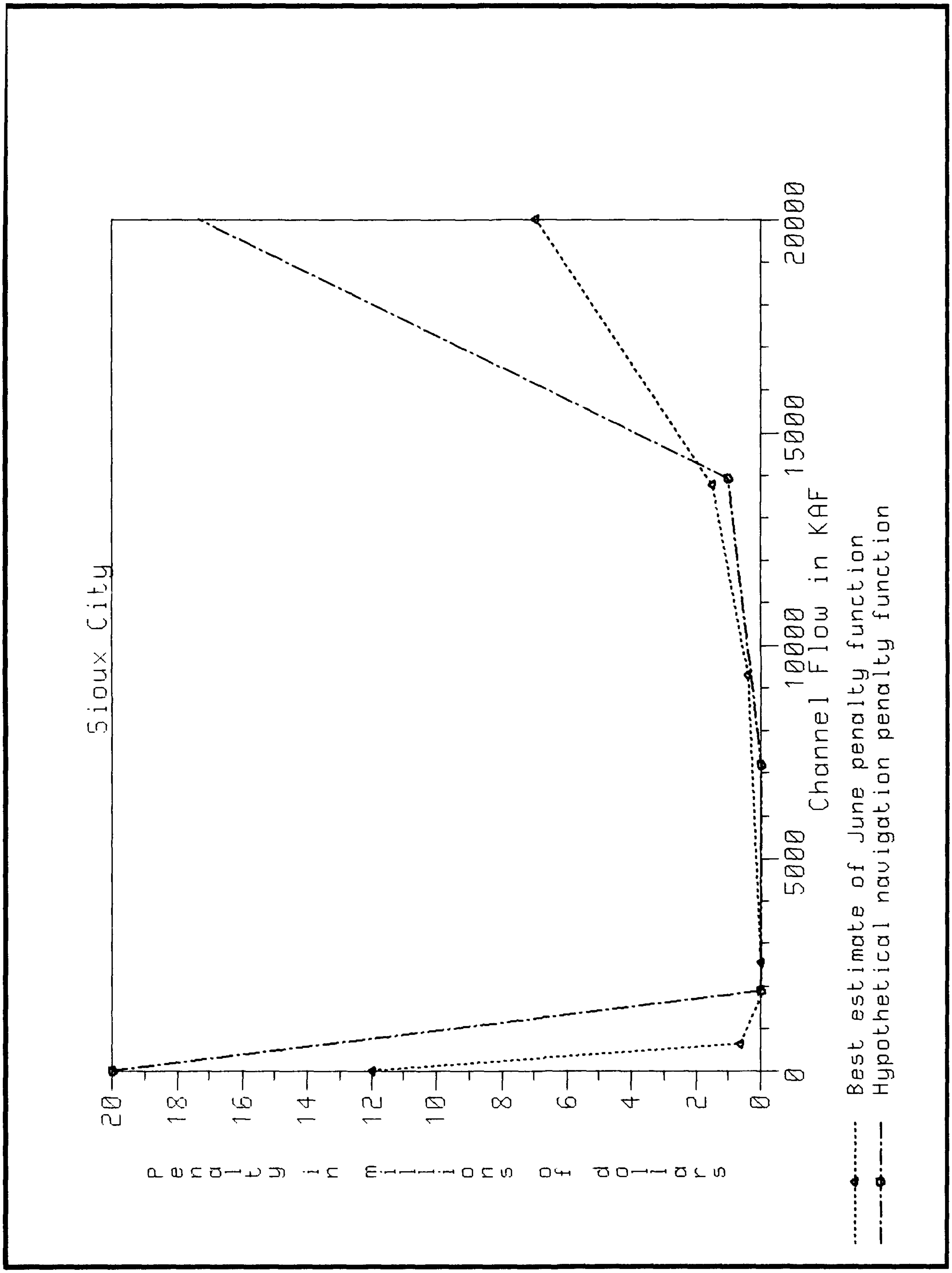


FIGURE 10 Sioux City Penalty Functions for Critical Period (June)

PHASE II ACTIVITIES

As proposed by HEC, Phase II of this study begins in January 1991. In Phase II, HEC and IWR staff will (1) expand the system analyzed; (2) refine the penalty functions used; (3) improve HEC-PRM's user interface; (4) make technical improvements to HEC-PRM; and (5) perform selected production runs with HEC-PRM. These activities will be completed in January-June 1991. Phase II analyses are scheduled for June and July 1991. HEC and IWR staff will conduct a workshop for MRD staff in fall 1991. HEC will provide there a working version of HEC-PRM and draft user's documentation. HEC will provide a draft Phase II report in mid-November 1991. HEC-PRM software, complete user documentation, and final Phase II report will be provided to MRD staff by 31 December 1991.

Model Expansion

The Phase I model includes all six main-stem reservoirs, but includes non-reservoir control points only as far downstream as Hermann. As needed, additional downstream reaches will be added in Phase II. To model well the impact of system operation on navigation, the system will be extended at least to St. Louis. Mississippi River navigation targets will be imposed there. The period of analysis will be expanded, if possible, to the available period of record.

Penalty Functions Refinement

The penalty functions used in Phase I are based on the best currently available data. For Phase II, these functions will be refined, and functions will be added to permit modeling operation for all purposes.

One area in particular will require additional effort: definition of penalty functions for reservoir flood-control storage. In Phase I, no penalty was associated with storing water in the flood-control pools of the system reservoirs. As HEC-PRM considers simultaneously operation for all periods, the minimum-penalty allocation may call for storing water in the flood control pool to meet downstream water-supply demands some months in the future. To avoid this operation, HEC-PRM was constrained in Phase I to prevent use of the exclusive flood-control pool. For Phase II, a penalty for using reservoir flood-control storage will be developed.

As originally proposed, refinement of the functions will be undertaken as a task separate from model development.

User Interface Improvement

The HEC proposal indicated that staff would "... generalize input, output reporting, and user interface for the model ..." In doing so, HEC staff will focus on automating penalty-function derivation, on standardizing the presentation of results, and on improving user-model interaction for system definition.

Penalty-function Derivation. HEC-PRM requires the user to specify no more than one penalty function for each system link. This function must be convex and piecewise linear. Consequently, the user must pre-process penalty functions developed for various project purposes to derive this function. For the applications reported herein, this pre-processing was done manually by HEC and IWR staff. For each link, the flood-control, hydropower, navigation, water supply, and recreation penalty functions were added. The resulting function was stored with the HECDSS (USACE, 1990g). The function was plotted, and a convex, piecewise linear approximation was defined "by eye." For a complex system, this is tedious, time-consuming, and subject to operator error.

For Phase II, the process of deriving the penalty functions of the required format will be automated. However, human interaction will be included in the final selection of the functions. For example, an algorithm may be developed to sum the functions and suggest a convex, linear approximation of the results. However, the suggested function will be displayed for the user to accept or reject. If the user rejects the suggested function, he or she will be able to define an alternative. If feasible, this will be done interactively, using a mouse or other pointing device.

Presentation of Results. Results of solution of the network-flow programming representation of the reservoir operation problem are stored with the HECDSS. The HEC DSPLAY program is used to plot any of these results, as desired by the user. This provides maximum flexibility for a knowledgeable user, but is overwhelming for the novice user. Accordingly, HEC will select, with concurrence of MRD, a set of standard displays. These standard displays will show pertinent hydrologic variables at selected locations. The displays will be pre-programmed and included so they are directly accessible from the user interface. At a minimum, the displays will include the reservoir storages and downstream flows for the period of analysis.

In addition to displays of hydrologic variables, HEC will select performance indices for display. Likely candidates are the time series of hydroelectric energy generated, cost-based penalty, and non-cost-based penalty at selected locations. Additional performance indices may be computed from the results. For example, flow-duration curves can be computed with data stored in HECDSS. If MRD staff identify such indices, procedures for developing them will be pre-programmed and included so they are directly accessible from the user interface.

Currently, HEC-PRM provides a minimum of tabulated results. HEC will expand HEC-PRM to provide tabulations consistent with other HEC reservoir analysis software.

User-model Iteraction For System Definition. In its current form, HEC-PRM is generalized. The system configuration is specified by the user. No assumptions are built into HEC-PRM regarding hydraulic interconnections, system inflows or outflows, or hydropower facilities. All system hydrologic and economic data are stored with the HECDSS. All results also are stored with the HECDSS.

Nevertheless, definition of the system may be simplified, especially through development of a graphical interface. Prof. J. Andreau of the Universidad Politecnica de Valencia (Spain) has developed such an interface for AQUATOOL, his reservoir system model. This interface uses the graphical interface tools of MS-Windows 3.0. Prof. Pete Loucks of Cornell University has developed a similar interface for his model, IRIS.

Loucks's interface uses CAPLIB routines from Resource Planning Associates. Both interfaces permit the user to "draw" a reservoir system on the PC monitor with a mouse. The system hydraulic linkages are inferred from the graphical representation. Both also feature "fill in the blanks" forms for specification of pertinent data. Working copies of AQUATOOL and IRIS are available at HEC. In Phase II, these and other user interfaces will be evaluated. An appropriate interface for HEC-PRM will be selected and implemented.

Capability for interactive data entry and editing of penalty functions, arc flow bounds, system constraints, and initial and final storages will be developed. Also, interactive control of HEC-PRM execution specifications, output reports, and displays will be developed.

Technical Improvement

HEC-PRM will be improved for Phase II studies. The hydropower algorithm will be fully-implemented. The execution time required will be reduced if feasible.

Hydropower Algorithm. For all applications in the Phase I study, hydropower penalty functions were simplified to express the penalty as a function of reservoir release only. For subsequent analyses, HEC-PRM will be improved to include the more complex relationship of hydropower penalty to release *and* head. A proposed algorithm for doing so is presented in the requirements document in Appendix C. Implementation of the algorithm will require some testing and additional development by HEC. The algorithm proposed is for hydropower value functions slightly different from the penalty functions provided by MRD.

Execution Time. The execution time of HEC-PRM is great by current standards for PC programs. For example, to analyze the critical period on a 25 mHz PC with 80486 processor requires 3.5 hours. If this is intolerable, execution time will be reduced by using a faster computer, reducing the number of arcs and nodes in the network, simplifying the formulation, or reformulating HEC-PRM to use a different solver.

(1) Using a Faster Computer. This is perhaps the simplest solution and may reduce the execution time as desired. Two possibilities exist: (1) Use a faster PC, such as a 80486 processor with a Weitek coprocessor; or (2) move the program from the PC to another USACE computer.

A shift to a PC with a Weitek coprocessor may solve the network faster. With a Weitek coprocessor, the execution time, according to published reports, may be halved. Other technical problems may arise if the Weitek coprocessor is used instead of the 80387. For example, certain programs that require a 80387 coprocessor will not use properly the Weitek coprocessor.

Much of the time required to solve the network problem is spent in simple calculations and in comparisons of parameters stored in arc-length arrays. The speed of these calculations and comparisons depends heavily on the speed with which these arrays can be addressed by the CPU. Under DOS, this is limited by the 640 kbytes directly-addressable memory. Beyond this limit, the operating system swaps pages of memory into and out of the 640 kbytes of memory. This is not required with other operating systems,

such as the UNIX system common on engineering workstations. With these operating systems, all memory is accessible directly from the CPU. Consequently, a shift to a machine with a less-restrictive operating system may solve the network faster. In addition, RISC chip based engineering workstations typically are substantially faster in processing speed than PC's.

Shifting HEC-PRM from DOS and the PC to another operating system or computer will require special attention to computer numerical accuracy. The algorithms used by the network solver are iterative algorithms. They rely on many thousands of comparisons of arc costs and arc flows. The accuracy of the computer plays a role in the accuracy of these comparisons. This numerical analysis problem must be addressed if a shift is made, and appropriate tolerances for the comparisons must be selected for each computer to be used.

(2) Reducing The Number of Arcs and Nodes in the Network. This is the nonstructural approach: If the solver takes too long, reduce the size of the problem. The most obvious way to do so is to limit the number of linear segments used in any piecewise approximation of the penalty functions. For example, the Missouri river system model has one reservoir-storage link for each month for each of the six reservoirs. If four arcs are required to represent the storage penalty function in each case, the total number of arcs required is 288 per year. If only three arcs are used, the number required is reduced by 25%. The same logic applies throughout the network: If the penalty functions are simpler, the network will be smaller, and the solution will be found quicker.

(3) Simplifying the Formulation. Significant execution time is required to account for the lake evaporation with currently-employed network solver. To reduce the execution time, this accounting may be simplified. One alternative is to specify the evaporation volume for each reservoir for each month prior to solution. In that case, the evaporation is treated as a diversion from the reservoir. The potential error is that the specified volume may be too large or too small for the computed lake surface area.

The alternative is to iterate to estimate the lake evaporation. In other words, HEC-PRM could estimate a fixed evaporation volume for each reservoir for each month, based on initial estimates of storage. These estimates are treated as diversions, and the network problem is solved. The fixed evaporation volume is compared then with the proper volume of evaporation from each reservoir each period. If the two are sufficiently close, iteration stops. Otherwise, the fixed volume is corrected, and the process is repeated. Even with three or four iterations, this may be faster than the network-with-gains algorithm.

A side benefit of simplifying the formulation as proposed is that it will be possible to use a faster network solver. A solver for a network with no gains (a pure network) may be 10 times faster that a solver for a network-with-gains (generalized network). Further, very large scale problems can be solved with the generalized network codes.

(4) Reformulating HEC-PRM to Use a Different Solver. This alternative requires reformulating HEC-PRM to use a different solver, such as a pure linear programming (LP) solver. This would require re-writing the code that sets up the arrays for the network solver. Instead of describing arcs and nodes, the code would specify the coefficients in a set of simultaneous linear equations. The code required would indicate the row and column number of each coefficient and the coefficient magnitude. The code would also specify the magnitude of the known right-hand side of each equation.

A variety of efficient LP solvers are available for the PC. Some, including the commercially-available CPLEX solver, are not limited at all by available computer memory. Others, such as the non-commercial XMP package used in program HEC-5Q, make efficient use of available computer memory.

Perform Selected System Analysis

In the interest of providing efficient analysis for the on-going Master Manual Update study, several key system analysis will be performed by HEC. System operation policy sets representing differing views will likely have surfaced by the time the full model capabilities are operational and prior to the development of the data input and output report components of the model. Three to four analysis are planned. One will be chosen to emphasize and illustrate operation for environmental goals such as sustaining endangered species. The results will be summarized for use in the Master Manual Update study.

APPLICATIONS GUIDE

HEC-PRM will be a tool for efficiently developing information about optimal allocation of water for the hydrologic record studied and the penalty functions specified. It is envisioned that successive executions of the model with systematic adjustments to the model constraints and penalty functions, will provide a substantive basis for deriving updated system operation rules. The rules inferred from study of HEC-PRM results would be tested and refined using the existing Missouri River reservoir simulation model. The strategy to employ in using HEC-PRM to develop the critical information and the appropriate analysis for inferring the operation rules will be developed and documented in the Applications Guide. The investigation will be a mutual undertaking with the MRD staff and will most likely evolve as a case study applications document.

CONCLUSIONS

From the activities of Phase I, HEC staff conclude the following:

- Network flow programming is an appropriate tool for analysis of long-term system operation. It is simple enough to understand in theory, yet sophisticated enough to account for most critical system characteristics and operation requirements.

- A usable model (HEC-PRM) has been implemented on the PC.

- The success of a prescriptive model such as HEC-PRM depends on the capability of the penalty functions to capture the essence of operation goals and constraints.

- Additional development is required before the results of HEC-PRM are "fit for public consumption." The work proposed for Phase II will yield a model and penalty functions that will provide useful information for making decisions regarding long-term operation rules for the MRD system.

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APPENDIX A

PROPOSAL FOR
APPLICATION OF SYSTEM ANALYSIS
TO MISSOURI RIVER MAIN STEM
MASTER WATER CONTROL PLAN UPDATE STUDY

By

Hydrologic Engineering Center

July 6, 1990

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PROPOSAL FOR
APPLICATION OF SYSTEM ANALYSIS
TO MISSOURI RIVER MAIN STEM
MASTER WATER CONTROL PLAN UPDATE STUDY

by
Hydrologic Engineering Center
July 6, 1990

SUMMARY

This proposal presents a plan to apply system analysis methods for the Missouri River Main Stem Master Water Control Manual Update study. We propose to:

a. Prepare a document assessing the applicability of network-flow programming system analysis method for the study,

b. On a trial basis, formulate and apply a network-flow model to the Missouri River main stem,

c. Develop and document preliminary project output value functions (penalty functions) for use with the model, and

d. Present the results in a Phase I summary report.

Following review and analysis of the trial model formulation and application, approval for Phase II would:

e. Expand the conceptual and geographic scope of the network-flow model to the full Missouri River Main Stem system and issues,

f. Refine the value (penalty) functions,

g. Perform several system analyses for selected policy options and prepare summary report,

h. Generalize input, output reporting, and user interface for the model,

i. Develop preliminary user documentation, and

j. Conduct workshop for MRD staff on model application.

Phase I will be completed in 6 months at a cost of $66,500. Phase II will be completed 12 months following Phase I and is estimated to cost $90,200 for a total cost of $156,700. The Phase II cost is preliminary and will be finalized following Phase I. Table A-1 lists the tasks and estimated staff time to accomplish. Figure A-1 presents the proposed project schedule.

BACKGROUND

The Missouri River System Master Water Control Manual Review and Update study is described in the Draft Phase I Report dated May 1990. The report describes the objective of the study, identifies a range of water control operations alternatives, and briefly describes potential economic, social, and environmental impacts of alternatives that merit further study. The principal determinants of system operation are presented as four decision criteria: 1) allocating system storage among exclusive flood control, flood control and multiple use, carryover and multiple use, and permanent pool; 2) navigation season length; 3) minimum winter discharge; and 4) minimum summer discharge. Choices resulting from these decision criteria have profound impacts on the system's performance in meeting purposes of flood control, hydropower, water supply, recreation, and navigation.

The study strategy presented in the Draft Phase I report is that of identifying alternative operating plans, evaluating the impacts of alternative plans, and based on these impacts and views of others, selecting a plan. System analysis methodology poses the problem in a different context given the system characteristics, system operation purposes, and impact relationships, develop the operating scheme that best accomplishes the system goals. The system hydrologic simulation, impact evaluation, and subsequent storage utilization and releases are formulated such that the computation results are the desired system operation.

System analysis methods develop information in a prescriptive rather than a descriptive manner. The results of the analysis are contingent on the ability to represent the essence of system performance and impacts such that the operation problem is formulated in a tractable structure and can be solved. The application proposed is to develop a tool that can provide information and insight into operation options and trade-offs that are not easily surfaced in the methodology currently being used. Implementing the system analysis model will not resolve the real conflicts that exist today - there is simply not enough water during drought years. It will assist in devising means for sharing negative impacts and developing long term strategies that are equitable among basin water resource system beneficiaries.

PROPOSAL

The tasks comprising the proposed work are described in following paragraphs.

a. **System Analysis Applicability Assessment.** A number of successful system analysis applications to reservoir system operation problems are reported in the literature. Texts, (see for example Loucks, et. al. 1981) and journal articles (Yeh, 1985) present a wide range of methods and applications examples of system analysis technology. Proposed applications to water resources system operations are many and are reported on a continuing basis in the literature. Few have achieved the status of practical applications.

Based on literature review, experience with similar studies, and consultation with system analysis experts, we propose to develop and apply a network-flow programming model to the Master Manual Update study. This task will develop a document describing the strengths and weaknesses of the

selected method. The document will be written with MRD and HQUSACE management as the target audience. An assessment of the application of the network-flow model to the study will be preformed as part of task d.

b. **Formulate and Apply Preliminary Model.** Examples of successful applications to problems similar to that of the Missouri River system are described in (Sigvaldason, April 1976) and (Chung et al, March 1989).

Network-flow programming, a special case of linear programming, is the system analysis method proposed for trial application to the Missouri River main stem system. This is the method discussed in these papers and described more extensively in (Jenson and Barnes, 1980). The D2M2 model (HEC, 1984), applies network flow-modelling to the problem of optimal transport and disposal of dredged-material. D2M2 was successfully developed by HEC and continues in use by the Philadelphia District.

The network-flow model will provide for hydrologic simulation and prescriptive operation of the Missouri River system. The model will be formulated on a monthly time-step with aggregation to longer periods for seasons for which monthly detail is not warranted. A network-flow model represents the system as a series of nodes and arcs. Each reservoir and each demand point is represented by a node. Flow is conserved at nodes. The hydraulic interconnect of reservoirs and demand points is represented by arcs between the nodes. These arcs have specified capacity. Functions are developed to relate flow in an arc to a measure of the value of the system output. For this application, a penalty function that can be thought of as the cost of flow in the arc, will be used. A penalty function defines the per-unit penalty of flow in the arcs. By structuring a network with parallel arcs between nodes, complex penalty functions can be used. Figure A-2 is an example network for a single reservoir and a downstream control point with local inflow and a diversion. The network is duplicated for each time step and is connected to the previous time step with arcs representing carryover storage. The complete network model is a set of nodes and arcs with associated Missouri River system physical features, flow paths, flow limits, penalty functions, and system inflows for each time step.

A solution for flows in the network is developed by a network solver. The resulting flows in the network arcs are then interpreted to physically meaningful terms for tabulation and display. The solution to the network is the minimum penalty (e.g. maximum value) routing of flows and represents period-by-period discharge and storage utilization. This is in effect a simulation of the operation of the system for optimum operation based on the physical description of the system, constraints applied to the arcs, and penalty functions specified.

The test application will involve constructing a preliminary network and using a commercially available network solver for the solution. It will likely prove desirable to construct the network for a limited portion of the complete period-of-record and selected physical components. The solution for

network flows will be interpreted and recast into tabulations and displays for report presentation.

c. **Develop Preliminary Penalty Functions.** The functions needed for the network model are relationships between flow in the arcs (releases/stream flow, reservoir storage) and penalty. The network is "solved", e.g. flow is routed, through the arcs to achieve an overall minimum penalty. We propose that the penalty functions be developed based on achieving desired or "optimum" service levels with a penalty for failing to do so. A penalty function may be estimated from failure cost. For example, for downstream water diversions for water supply and cooling water, the cost of extending intakes or acquiring an alternative water supply for flow less that full service flow is computed and related to the flow in the Missouri at the diversion location. Flow below the target service level result in a penalty being incurred. The penalties for each diversion are aggregated by stream reach and related to flow. Similar logic is applied for river flow for recreation, power generation, and navigation, and for reservoir storage for recreation and fisheries purposes. To reflect operations desirable for environmental purposes such as enhancing the habitat of an endangered species, a penalty function can be devised and adjusted to cause operation of the system to occur in the desired manner.

The project purposes described in the Draft Phase I report are hydropower, flood control, water supply, recreation, and navigation. For the trial application, we propose to develop preliminary penalty functions for all these purposes for the Missouri River system for which data are readily available. Figure A-3 presents stylized penalty functions for flood control, water supply, navigation, hydropower, and reservoir recreation as examples.

d. **Phase I Summary Report.** The results of tasks a. - c. will be presented in a brief summary report. A technical appendix will describe the model development and application. Several experts in the field of system analysis will be asked to review the technical report and comment on the development and application of the network-flow model for the study.

The main report will describe the trial application and the model applicability to the full Missouri River system and issues assessed. The scopes of the remaining tasks for the successful accomplishment of Phase II will be refined from those presented in this proposal. The report will be written for the target audience of MRD, HQUSACE, and local agency managers and officials.

The Phase II tasks described below are contingent upon acceptance of the results of the Phase I effort. To a substantial degree, the efforts needed to successfully accomplish the tasks are dependent on findings of the Phase I studies. The assumption here is that the test application proves successful and that the test adequately demonstrates the usefulness of the model in the Master Manual Update study.

e. **Expand Model to Full System and Issues.** This task will expand the model to include as needed, additional upstream reservoirs, intervening and downstream reaches, and system operation purposes. Should the linear approximations employed in the test application need refinement, additional arcs will be added to refine the function definition. The full-flow record will be implemented. Methods to account for depletions resulting from future diversions, and permit analysis of selected time windows of the historic record will be developed. The construction of the model and data preparation will be documented in a technical report.

f. **Refine Penalty Functions.** The penalty functions used in the test application are based on available data. The functions will be expanded to include all purposes, all stream reaches, and all reservoirs. They will be refined based on specific research efforts undertaken to improve their reliability. These research efforts will be undertaken as a task separate from the model development project addressed by this proposal. The full scope of this task is highly dependent on the credibility of the functions adopted for the test application and the performance of the model regarding sensitivity of modelled system operations to changes in penalty functions.

g. **Perform Selected System Analysis.** In the interest of providing efficient analysis for the on-going Master Manual Update study, several key system analysis will be performed by HEC. System operation policy sets representing differing views will likely have surfaced by the time the full model capabilities are operational and prior to the development of the data input and output report components of the model. Three to four analysis are planned. One will be chosen to emphasize and illustrate operation for environmental goals such as sustaining endangered species. The results will be summarized for use in the Master Manual Update study.

h. **Develop Generalized Network Model Construction Capability and User Interface.** Construction of the network model for the Missouri River system to this point of the study will be crafted to the system, data, and issues initially defined. Modification of the model for additional and subsequent studies would require the services of a system analysis specialist to implement. To make the model generally usable for MRD staff and others, an automated network construction algorithm must be developed, and data input, output report development, and general user interface must be implemented. This will provide the capability for the user to describe the problem and data in commonly understood terms using familiar data without knowledge of the technical details of the network model. This concept was implemented by HEC for the D2M2 model and proved to be essential for the continued use of the model by the Philadelphia District.

i. **Preliminary User Documentation.** A draft user's manual will be prepared as a companion to the technical report described above in the section "e. Expand Model to Full System and Issues." The manual will describe the capabilities and limitations of the model, summarize the technical methodology, provide an input description, output explanation, and include a

test example application. The manual will be prepared in the style of existing HEC user's manuals.

j. **Workshop.** A two to three day workshop on model application will be formulated and presented to MRD and other interested local staff on-site in Omaha. The workshop will include presentations and discussions on data development, data entry, program applications, and output analysis. The model will be used in workshop sessions.

RESPONSIBILITIES, COORDINATION, AND MANAGEMENT

The system analysis model development and application project will be performed by the Hydrologic Engineering Center for the Missouri River Division. HEC will rely on the Institute for Water Resources for the development of the penalty functions. IWR will assist in the network construction and act as advisor on other aspects of the project. Oversight will be provided by HQUSACE engineering and planning divisions. The project will be coordinated on a continuing basis with check point meetings as shown on the schedule in Figure A-1. Attendance by all project participants will be encouraged. Substantial assistance will be required from the Missouri River Division in several areas.

MISSOURI RIVER DIVISION RESPONSIBILITIES

MRD will:

* Provide detailed definition of the requirements of the system analysis application to the Master Manual Update study,

* Furnish hydrologic data of monthly flows for system and local inflow,

* Provide physical descriptive data on the reservoir system, Missouri River, system diversions, target flow requirements, etc. The specific needs will be agreed upon in consultation with MRD staff,

* Provide cost data needed to construct the penalty functions, and

* Provide consultation and guidance on a continuing basis during the performance of the project.

RELATIONSHIP TO ON-GOING STUDIES

We will make a concerted effort to avoid undue interference with ongoing Master Manual Update studies. Additional effort to that presently planned by Missouri River Division staff for the Master Manual Update study will likely be required for the system analysis methodology application project to make a meaningful contribution to the study.

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TABLE A-1
TASK SUMMARY
*****Phase I*****

Task	Staff-days
a. Network-flow model applicability assessment	
b. Formulate/apply network-flow model - define preliminary system requirements - formulate network model - compile hydrologic, system data - generate network - secure, test network solver - apply test, interpret results	
c. Develop penalty functions - specify functions, define data needs - compile data, formulate functions - test functions - document development, application	
d. Prepare summary report, Phase II work plan	
* Management, travel, coordination, briefings	
SUBTOTAL PHASE I	110
*****Phase II*****	
e. Expand model to full MRD system, issues - complete system requirements specification - expand network model - arcs, nodes, etc. - complete data compilation, data entry - test expanded model - prepare technical report	
f. Refine and finalize penalty functions - complete function specification - update and incorporate additional data - prepare technical, applications documentation	
g. Perform selected system analysis (assume 4)	
h. Network generator and user interface - specify/develop network generator - design user interface, reports - develop user interface	
i. Preliminary user documentation	
j. Workshop	
* Management, travel, coordination, briefings	
SUBTOTAL PHASE II	163
GRAND TOTAL	273

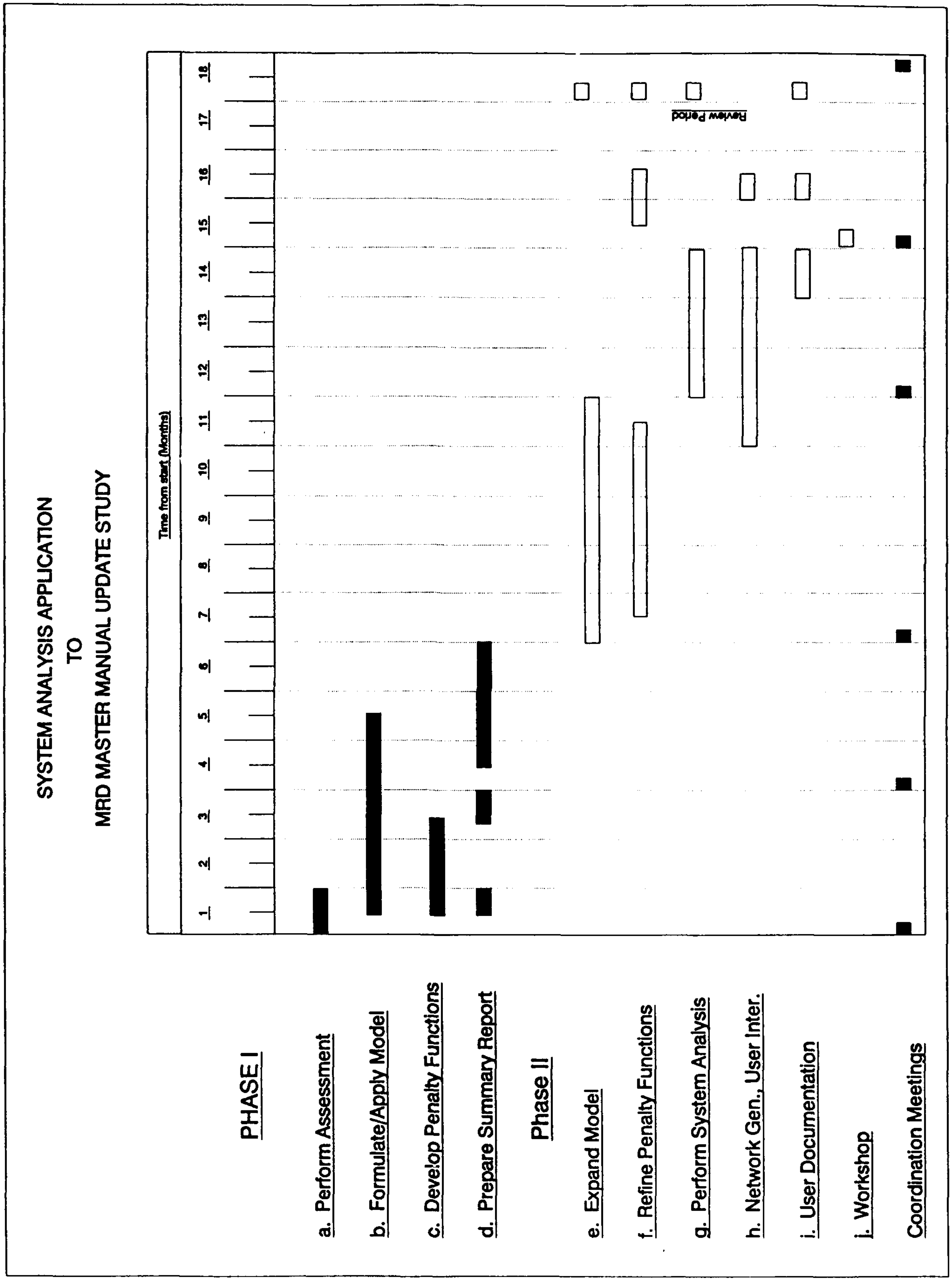

FIGURE A-1 Study Schedule

APPENDIX B

IS A NETWORK-FLOW PROGRAMMING MODEL THE RIGHT MODEL FOR ANALYSIS OF THE MISSOURI RIVER MAIN STEM RESERVOIR SYSTEM?

APPENDIX B

IS A NETWORK-FLOW PROGRAMMING MODEL THE RIGHT MODEL FOR ANALYSIS OF THE MISSOURI RIVER MAIN STEM RESERVOIR SYSTEM?

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APPENDIX B

IS A NETWORK-FLOW PROGRAMMING MODEL THE RIGHT MODEL FOR ANALYSIS OF THE MISSOURI RIVER MAIN STEM RESERVOIR SYSTEM?

CONCLUSION

A network-flow programming model is appropriate for analysis of the Missouri River main stem reservoir system because it satisfies institutional, economic, environmental, and engineering criteria. A network model represents the system operation problem with a set of nodes and arcs. A network solver finds the optimal allocation of available water to the arcs, subject to absolute limitations on that allocation. The network model demonstrates what will happen if a particular operation policy is adopted, and will indicate the policy preferred, given a set of priorities for operation.

WHAT IS A NETWORK-FLOW MODEL?

A network model represents the pertinent characteristics of a reservoir system, the objectives of operation, and limitations on actions with a set of simultaneous linear equations. The variables in the equations represent decisions that must be made by system operators. For example, the reservoir releases and storages are represented by variables in the equations. The equations that describe relationships of these variables are of three types: (1) An objective function equation; (2) continuity equations; and (3) upper and lower bounds on the variables. For convenience, the set of equations and the decision variables can be represented by a graph of nodes connected by directed arcs. Nodes represent river or channel junctions, gage sites, monitoring sites, reservoirs, or water-demand sites. Flow is conserved at these nodes: The total volume of water in the arcs originating at any node must equal the total volume in arcs terminating at that node. Arcs represent river reaches or diversion channels. Water moves from node to node through the arcs. A penalty (cost) is incurred for each unit of water that moves through an arc. Each arc is capacitated. That is, each has a minimum and a maximum flow that it must carry.

The proposed network model of the Missouri River main stem system is a layered model, with each layer representing one time period (one month in the model proposed). To develop this model, the network representation is developed first for a single month. Figure B-1 illustrates a simplified version of this network. Node 3 is a reservoir. Node 4 is a downstream demand point. The arc from node 3 to node 4 represents the total reservoir outflow. Node 1 is a hypothetical node that provides all water for the system. The arc from node 1 to node 3 represents the reservoir inflow. The arc from node 1 to node 4 represents the local runoff downstream of the reservoir. Node 2 is the hypothetical sink for all water from the system. The arc from node 4 to node 2 carries water from the reservoir/demand point network to this sink.

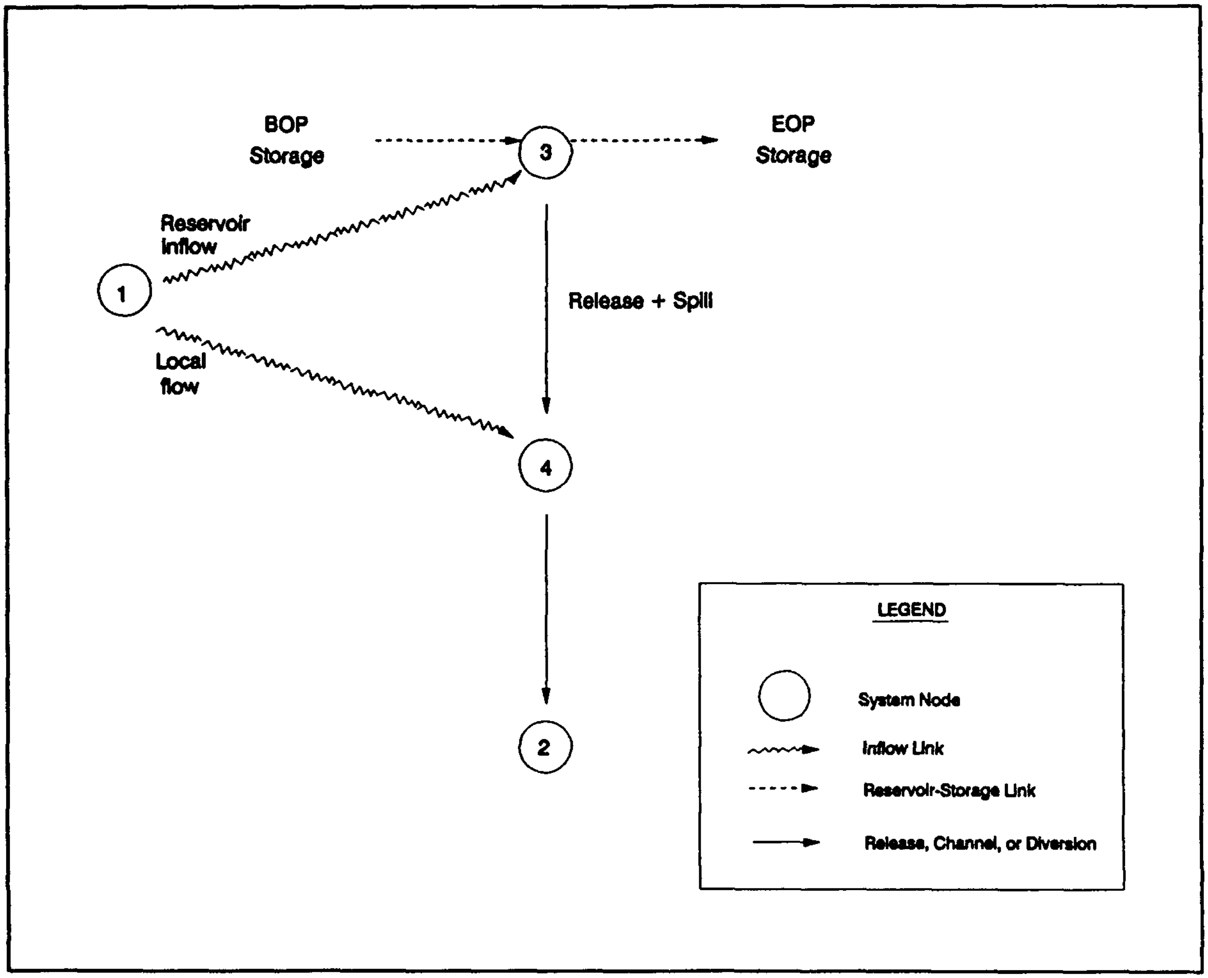

FIGURE B-1 Simplified Single-period Network

For each time period to be analyzed, the arc-node representation of the reservoir system is duplicated. Figure B-2 illustrates this. A single source node (node 1) and a single sink node (node 2) are included. The duplicate networks are connected by arcs that represent reservoir storage. For example, in Figure B-2, the arc connecting node 3 in period 1 to node 3 in period 2 represents the storage. The flow in this arc is the end-of-period 1 (beginning-of-period 2) storage. Likewise, the flow in the arc connecting node 3 in period 2 to node 3 in period 3 represents the end-of-period 2 storage. The single source node (node 1) and single sink node (node 2) are excluded from the figure for clarity.

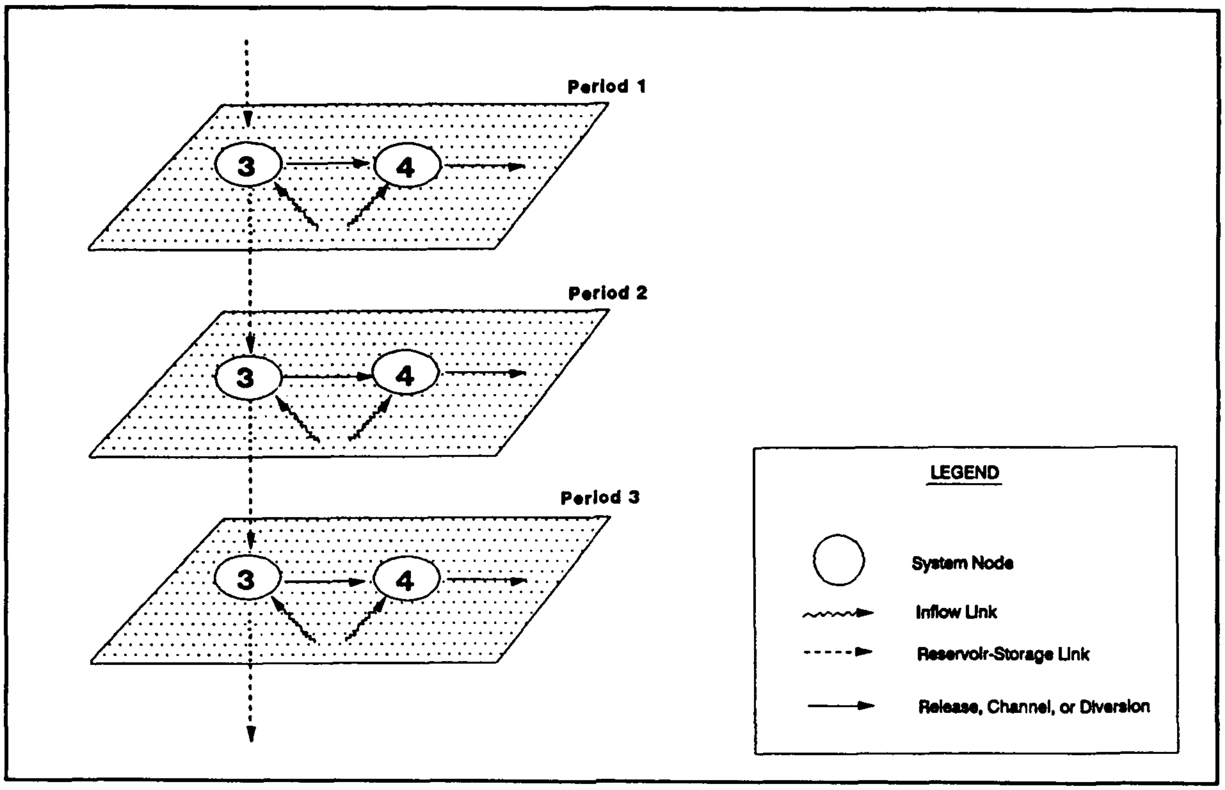

FIGURE B-2 Multiple Period Network

The optimal allocation of water in the layered network is determined with a network solver. The solver finds the flow in each network arc that yields the total minimum-penalty circulation for the entire network, subject to the continuity and capacity constraints. These flows may be translated into reservoir releases, hydropower generation, storage rates, diversions, and channel flows.

IS A NETWORK-FLOW PROGRAMMING MODEL THE RIGHT MODEL?

Institutional Criteria

Will the model solve the Missouri River main stem reservoir system operation problem? The network model proposed will provide information that will help solve the system-operation problem. However, the model itself will not solve explicitly the problem. No model can do that. The network model will help the policy makers and their staffs understand the consequences of proposed courses of action. For example, Hitch and McKean (1960) write, "casually selected or arbitrary constraints can easily increase system cost or degrade system performance manyfold, and lead to solutions that would be unacceptable to the person who set the constraints in the first place." The proposed model will demonstrate clearly the penalty for constraints (limitations) or degradation of system performance, as it is a penalty-driven model. This information will enable rational policy debate. The model will demonstrate what will happen if a particular policy is adopted, and will indicate the policy preferred, given a set of priorities for operation.

Can the model represent all system operation purposes fairly? Yes, the model can represent all operation purposes if system performance for those purposes is expressed in hydrologic terms. The penalties for flow in the network arcs are related to system releases, storages, and water deliveries. Likewise, the arc capacities are related to releases, storages, and water deliveries. Any purpose can be represented in the model in terms of these penalties and arc capacities. Solution of the network problem indicates how water is allocated for the various system purposes.

Can the model evaluate alternative priorities for system operation? Yes, alternative priorities can be evaluated by altering the arc penalties. The desirability of release, storage, and delivery dictates the magnitude of the penalty. The penalty factor is inversely associated with priority. For example, if storage in a reservoir is highly desirable, the penalty is low. If the storage is undesirable, the penalty is great. The relative magnitudes of the penalties dictate how water is allocated optimally in the network. To change priorities, the penalties are adjusted.

Will decision makers accept the results of this model? It is impossible to guarantee that decision makers will accept the results. However, the model has characteristics that increase the likelihood of acceptance. The first is simplicity. Woolsey (1975) suggests that people would rather live with a problem they cannot solve than accept a solution they cannot understand. The network approach is intuitive, and the solution procedure is straightforward. Consequently, decision makers should be able to understand the model. This should lead to acceptance of the results. The second important characteristic is realistic expectations. The results of the proposed model are not promoted as solutions to the operation problem. Instead, the results are promoted as information for rational policy debate. The third important characteristic is relevance. The proposed model will include, in some fashion, all purposes and priorities that can be identified. Finally, the model is flexible, and thus should be useful for answering, in a timely fashion, any "what-if" questions that may be raised by decision makers.

Can the model outputs be translated into terms that are readily understandable to users? Yes, the outputs can directly be translated to hydrologic terms. Further, the penalties can be used for direct, quantitative comparison of alternative operation priorities.

Can the model be modified or expanded easily as more information becomes available, as understanding of the system operation improves, and as the users become more sophisticated? The network structure of the model makes modification especially convenient. With alternative mathematical-programming tools, equations must be developed in a specific format. If the formulation changes, the equations change. When the equations change, computer code must be modified extensively to solve the resulting equations. This is not so with the network model. Modification of the network formulation requires only identification of new nodes and arcs and specification of the new arc parameters.

Can the model be used on the computer hardware available to users? The model will be developed specifically for use on the computer hardware available to MRD staff. Initial planning for the model indicates implementation on a state-of-the-art PC (80386 processor with expanded memory) may be possible. Such implementation would permit use of the model by interested government and nongovernment parties.

Can the model be implemented in time to provide information for decision making? Yes, the model will be developed in time to provide the information. The technology proposed is not experimental. It has been tested thoroughly and applied to similar problems (see references that follow). The model developers, the Hydrologic Engineering Center (HEC) staff, are not novices in model development. They have a 25-year history of success. The system analysis specialists, again the HEC staff, are not tinkering with new tools. They previously have used network-flow programming to solve water management problems. The model users, the MRD staff, are not new to modeling. They have used computerized system analysis models to study the Missouri River main stem for years. These all point toward successful implementation in a timely manner.

Economic Criteria

Can the model evaluate accurately the economic impact of operation decisions? The network model will evaluate the economic impact of operation decisions to the extent that the penalties assigned to flow in the network arcs are related to economic costs. Otherwise, the evaluation is in terms of relative satisfaction of demands for water.

Can the economic data required for the model be obtained with reasonable effort? The data required for economic analysis with the network model are the same data that would be required for economic analysis with any model of the reservoir system. Costs and benefits must be related to hydrologic parameters. This task is difficult. However, it is not a task unique to application of the network model.

Environmental Criteria

How can the model treat non-quantifiable operation purposes, such as fish and wildlife protection? The model treats non-quantifiable operation purposes through assignment of the penalties for flow in the network arcs. These penalties are not direct dollar costs. Instead, they are units of relative dissatisfaction, related to hydrologic phenomena. The penalty magnitude is assigned by the analyst. Consequently, the analyst can assign a penalty as large as required to achieve desired flows or storages for fish and wildlife protection. The model will demonstrate the trade-offs with other purposes as these penalties are adjusted.

Alternatively, the flow in network arcs can be constrained absolutely as required, for example, for fish and wildlife protection. This is accomplished by specifying discharge or storage requirements as upper or lower bounds on flow in appropriate network arcs. The network solver will find the optimal allocation of flow, given the absolute constraints, if a solution is possible. The difference in total system penalty with the constraint and without the constraint is the penalty for maintaining flow at the required level.

Can the model represent adequately the requirements for endangered species? The network model can represent the requirements in terms of monthly average discharge or storage. As described above, the requirements can be expressed in terms of penalties or as absolute limitations.

Engineering Criteria

System analysis is no longer restricted to "either it's linear or I can't do it," so why chose a linear model? A model may be developed with one of two alternative approaches. The first approach is to develop the model with realism uppermost, trying to simulate the real world to perfection. The alternative approach, followed here, is to keep relevance uppermost. This permits the questions asked, as well as the processes to be modeled, to determine what will be in the model. Of course, it is true that all engineering, economic, and environmental relationships are not linear in the Missouri River system. Nevertheless, a linear model will provide information about trade-offs amongst purposes and impacts of institutional, engineering, economic, and environmental limitations. These are the questions of interest.

Does the model use existing data or data that can be obtained with reasonable effort? The network model, as presently proposed, requires much of the same data as the existing MRD reservoir system simulation model. For example, reservoir characteristics, channel capacities, and diversion requirements must be defined. These data are readily available. Likewise, the flow data required are the same as required by the existing MRD simulation model.

Can alternative future inflow or demand sequences be studied conveniently? The network model will be developed so inflows and demands are defined with input. Alternative sequences can be studied by changing only input. The network configuration will remain unchanged.

Can the model account for risk? The network model does not account for risk explicitly. However, it is possible to account for risk implicitly by analyzing the frequency of various network-model results. For example, the network model may be applied to determine the optimal allocation of water for the 92-year historical record, given a set of penalty functions. As a consequence of this application, the monthly-average channel discharge time series is computed. The channel discharge-frequency curve can be computed with this time series. The frequency curve will account for risk of failing to meet discharge demands. Similar frequency analyses can be made for reservoir release, power generation, diversion flow, or other pertinent variables. To increase the reliability of the statistical analyses, alternative inflow and demand sequences can be developed with a stochastic-hydrology model and analyzed with the network model.

Is the technology dependable? Yes, the technology for formulating and for solving network-flow programming problems is dependable. Representation of water-management problems as network-flow problems is well-known. The Texas Water Development Board (TWDB) developed network models for studying alternative state water plans in the 1970's (TWDB, 1974). Sigvaldason (1976) used a network model to plan operation of the Trent river system, Canada. The California Department of Water Resources uses network models for planning (Chung, Archer, and DeVries, 1989) and for real-time operation of the State Water Project (Sabet, et al., 1985). Ikura and Gross (1984) formulated a network model for scheduling operation of a hydroelectric system. HEC formulated a "leaky" network and employed a network-with-gains algorithm to analyze dredged-material disposal management (Corps of Engineers, 1984; Ford, 1986).

Network solvers were introduced in the 1960's (Ford and Fulkerson, 1962; Durbin and Kroenke, 1967) and have been widely used. Subsequent research has yielded solvers that are faster than the original solvers (Barr, Glover, and Klingman, 1974) and solvers for more general network problems (Jensen, Bhaumik, and Driscoll, 1974; Jensen and Barnes, 1980).

Is the network-solver fast enough? Network solution algorithms are amongst the fastest mathematical-programming algorithms. Even on the PC, these algorithms have the reputation of solving problems in one-tenth the time required for solution with a linear-programming algorithm. Jensen, Bhaumik, and Driscoll (1974) show results that indicate for some problems the network-with-gains solves some problems in one-hundredth the time required for an linear-programming algorithm.

SUMMARY

A network-flow programming model is proposed for analysis of operation of Missouri River main stem reservoir system operation. This model represents the relevant institutional, economic, environmental, and engineering features of the system with a set of nodes and arcs. Penalties are assigned for flow in the arcs. A network solver finds the minimum penalty allocation of water to the arcs.

The model proposed will represent all relevant project purposes. It will use readily-available hydrologic data. It will use economic data consistent with those that must be collected for any evaluation. Model results can be translated easily into terms that are understandable to users.

The proposed model will quantify the impacts of alternative operation priorities, and it will quantify the impacts of absolute limitations on discharge and storage. In this manner, it will provide information for rational policy debate.

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APPENDIX C

REQUIREMENTS FOR PRESCRIPTIVE MODEL OF MISSOURI RIVER MAIN STEM RESERVOIR SYSTEM OPERATION

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REQUIREMENTS FOR PRESCRIPTIVE MODEL OF MISSOURI RIVER MAIN STEM RESERVOIR SYSTEM OPERATION

SUMMARY OF REQUIREMENTS

The Missouri River main stem reservoir system operation problem will be addressed as a problem of optimal long-term allocation of available water. A prescriptive model will be developed to solve this problem. The model will identify the allocation that minimizes poor performance for all defined system purposes. Performance will be measured with analyst-provided penalty functions of flow or storage or both.

To determine the optimal water allocation, the physical system will be represented as a network, and the operating problem will be formulated as a minimum-cost network flow problem. The objective function of this network problem is the sum of convex, piecewise-linear approximations of the penalty functions. An off-the-shelf solver will be used to define the optimal allocation of water within the system. The results of the solver will be processed to report and display reservoir releases, storage volumes, channel flows, and other pertinent variables.

To the extent possible, the software to implement the model will be general purpose. Accordingly, the software will include the following model-building components:

1. Inflow link;
2. Initial-storage link;
3. Diversion link;
4. Final-storage link;
5. Channel-flow link;
6. Simple reservoir-release link;
7. Hydropower reservoir-release link;
8. Reservoir-storage link; and
9. Node.

An analyst can specify the characteristics of and the configuration of these components to represent any system.

PROBLEM STATEMENT

The problem addressed by the proposed system model is identification of the optimal long-term operation plan for the reservoirs of that system. This plan will identify the priorities to be assigned to conflicting objectives of operation. For example, the plan will identify whether water should be released from a system reservoir if a demand exists for downstream flow for wildlife protection and a conflicting demand exists for continued storage of the water for reservoir recreation.

The model will quantify system performance for various purposes in multi-objective terms. The economic cost of operation will be considered. Also, the social and environmental cost will be considered. These costs will be expressed in commensurate terms to permit display of trade-offs in operation for various purposes.

Constraints on the physical system will be included. For example, the outlet capacity of the reservoirs will be modeled explicitly. However, inviolable constraints on system operation will used frugally. This will avoid the problem described by Hitch and McKean (1960) when they wrote "...casually selected or arbitrary constraints can easily increase system cost or degrade system performance manyfold, and lead to solutions that would be unacceptable to the person who set the constraints in the first place." Instead, operation limitations will be imposed through value functions. This will permit clear evaluation of the impacts of limitations. For example, instead of specifying maximum flow requirements for flood control, the system model will represent this requirement through high costs of failure to meet the requirement.

PROPOSED SOLUTION

The proposed solution considers the reservoir operation planning problem as a problem of optimal allocation of available water. The proposed solution to this water allocation problem is as follows:

(1) Represent the physical system as a network;

(2) Formulate the allocation problem as a minimum-cost network flow problem;

(3) Develop an objective function that represents desirable operation;

(4) Solve the network problem with an off-the-shelf solver; and

(5) Process the network results to define, in convenient terms, system operation.

Represent System as a Network

For solution of the water allocation problem, the reservoir system will be represented as a network. A network is a set of arcs that are connected at nodes. The arcs represent any facilities for transfer of water between two points in space or time. For example, a natural channel transfers water between two points in space and is represented by an arc. A reservoir transfers water between two points in time; this transfer is represented by an arc.

Network arcs intersect at nodes. The nodes may represent actual river or channel junctions, gage sites, monitoring sites, reservoirs, or water-demand sites. Flow is conserved at each node: the total volume of water in arcs originating at any node equals the total volume in arcs terminating at that node.

Figure C-1 illustrates a simple network representation. Node 3 represents a reservoir. Node 4 represents a downstream demand point. Two additional nodes with associated arcs are included to account completely for all water entering and leaving the system. Node 1 is the source node, a hypothetical node that provides all water for the system. Node 2 is the sink node, a hypothetical node to which all water from the system returns. The arc from node 1 to node 3 represents the reservoir inflow. The arcs shown as dotted lines represent the beginning-of-period (BOP) and end-of-period (EOP) storage in the reservoir. The BOP storage volume flows into the network from the source node. The EOP volume flows from the network back to the sink node. The arc from node 3 to node 4 represents the total reservoir outflow. The arc from node 1 to node 4 represents the local runoff downstream of the reservoir. The arc from node 4 to node 2 carries water from the reservoir/demand point network to the sink.

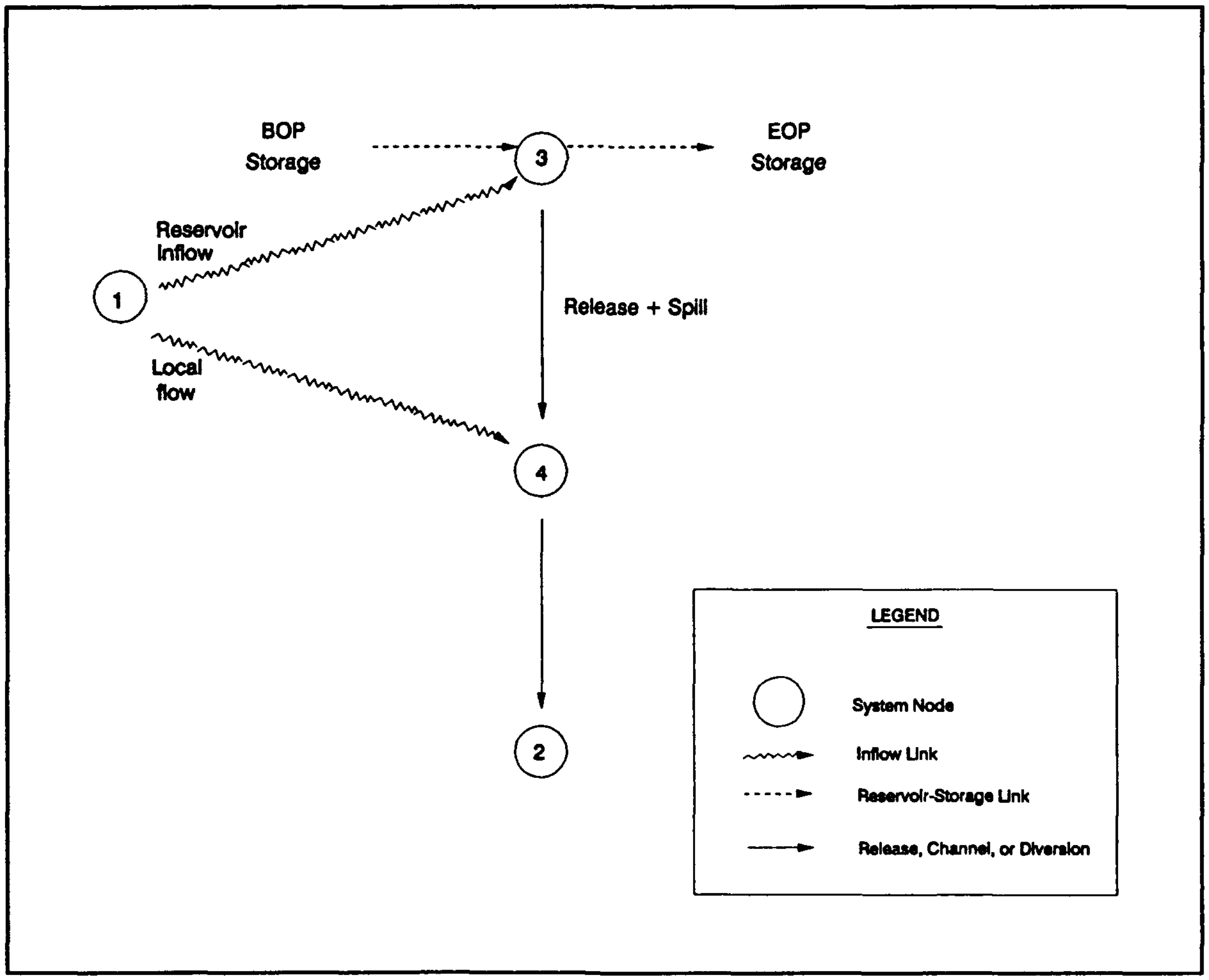

FIGURE C-1 Simplified Single-period Network

To analyze multiple-period system operation, a layered network will be developed. Each layer represents one month. To develop such a layered network, the single-period network representation is duplicated for each time period to be analyzed. Figure C-2 illustrates this. A single source node and a single sink node are included. For clarity, these have been omitted from the figure. The duplicate networks are connected by arcs that

represent reservoir storage. For example, in Figure C-2, the arc connecting node 3 in period 1 to node 3 in period 2 represents the storage. The flow along this arc is the end-of-period 1 storage. This is equivalent to the beginning-of-period 2 storage. Likewise, the flow along the arc connecting node 3 in period 2 to node 3 in period 3 represents the end-of-period 2 storage. This also is the beginning-of-period 3 storage.

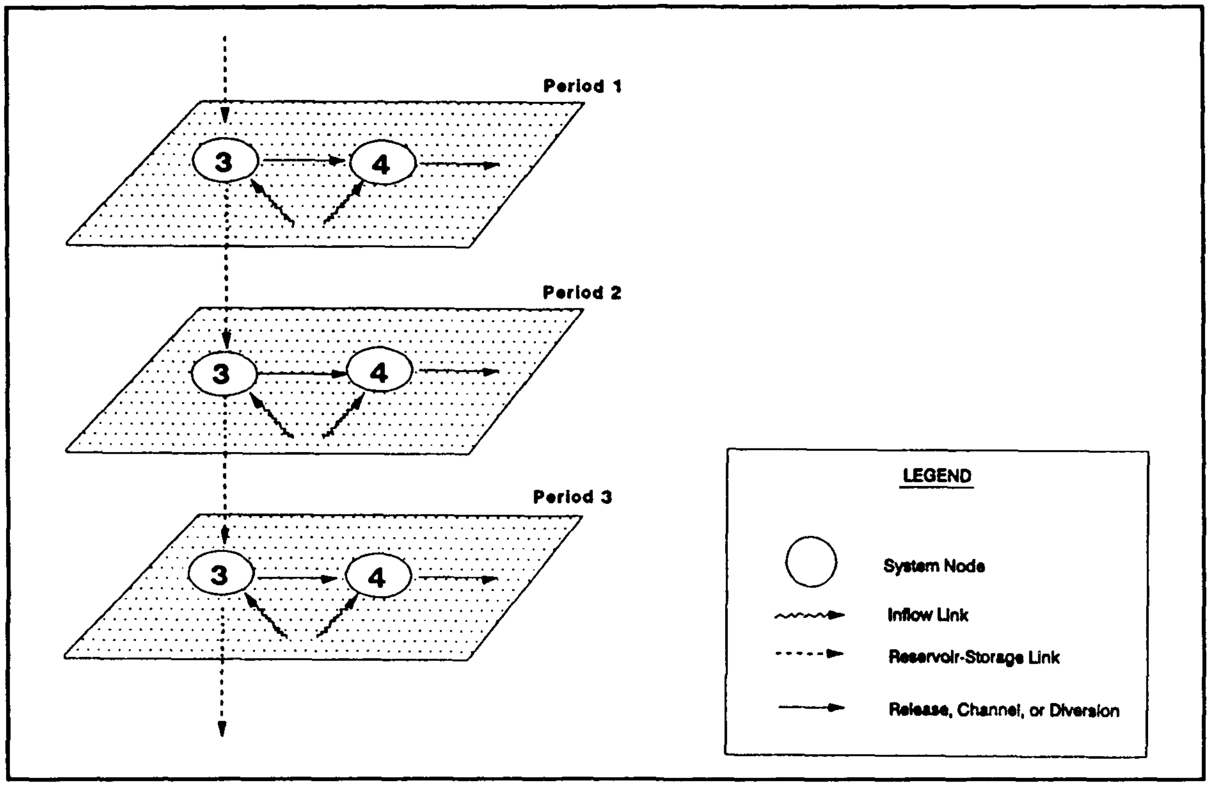

FIGURE C-2 Multiple Period Network

Formulate the Allocation Problem as a Minimum-cost Network-flow Problem

The goals of and constraints on water allocation within the reservoir system can be represented in terms of flows along the arcs of the network. If a unit cost is assigned for flow along each arc, the objective function for the network is the total cost for flow in all arcs. The ideal operation will be that which minimizes this objective function while satisfying any upper and lower bounds on the flow along each arc. The solution also must maintain continuity at all nodes.

Minimum-cost Objective Function. A network solver finds the optimal flows for the entire network simultaneously, based on the unit cost associated with flow along each arc. The functions that specify these costs are defined by the analyst.

The simplest cost function is a linear function, such that shown in Figure C-3. This function represents the cost for flow along one arc of a network. The cost increases steadily as the flow increases in the arc. The unit cost is the slope of the function. Here, it is positive, but it may be positive or negative. The total cost for flow along the arc represented is the product of flow and the unit cost.

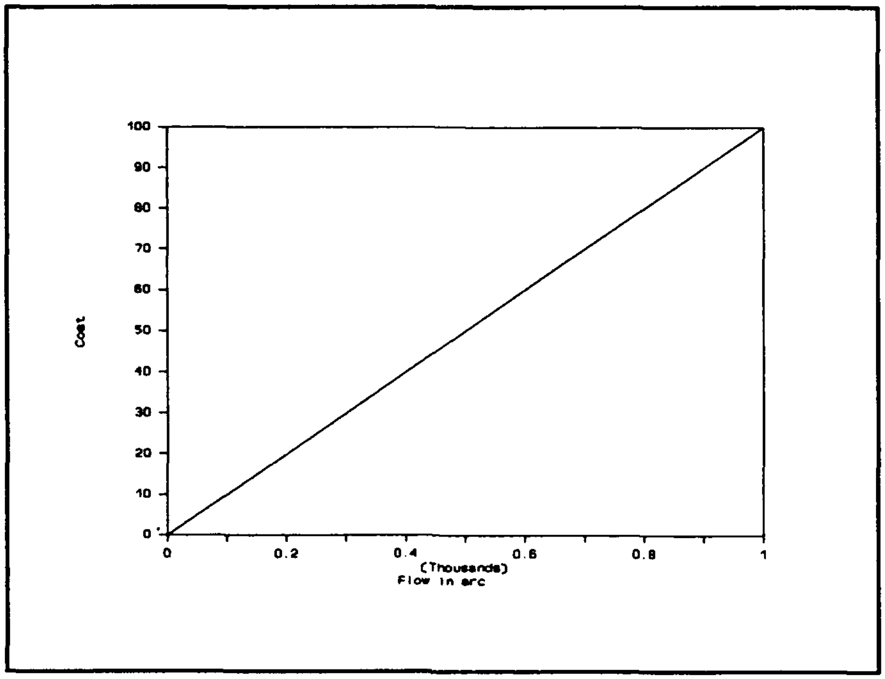

FIGURE C-3 Simple Linear Cost Function

The simplest linear function may be too simple to represent adequately many of the goals of reservoir operation. Instead, nonlinear functions, such as those shown in Figures C-4(a-c), may required.

Piecewise-linear Approximation. If the cost functions are convex, as are those in Figures C-4(a-c), they can approximated in a piecewise linear fashion for the proposed network model. Figure C-5 illustrates piecewise approximation of a complex cost function. Linear segments are selected to represent the pertinent characteristics of the function. The analyst controls the accuracy of the approximation. More linear segments yield a more accurate representation. However, the time required for solution of the resulting network-flow programming problem depends on the number of arcs included in the network. Thus, as the approximation improves, the time for solution increases. Jensen and Barnes discuss this approximation in detail (1980, pgs. 355-357).

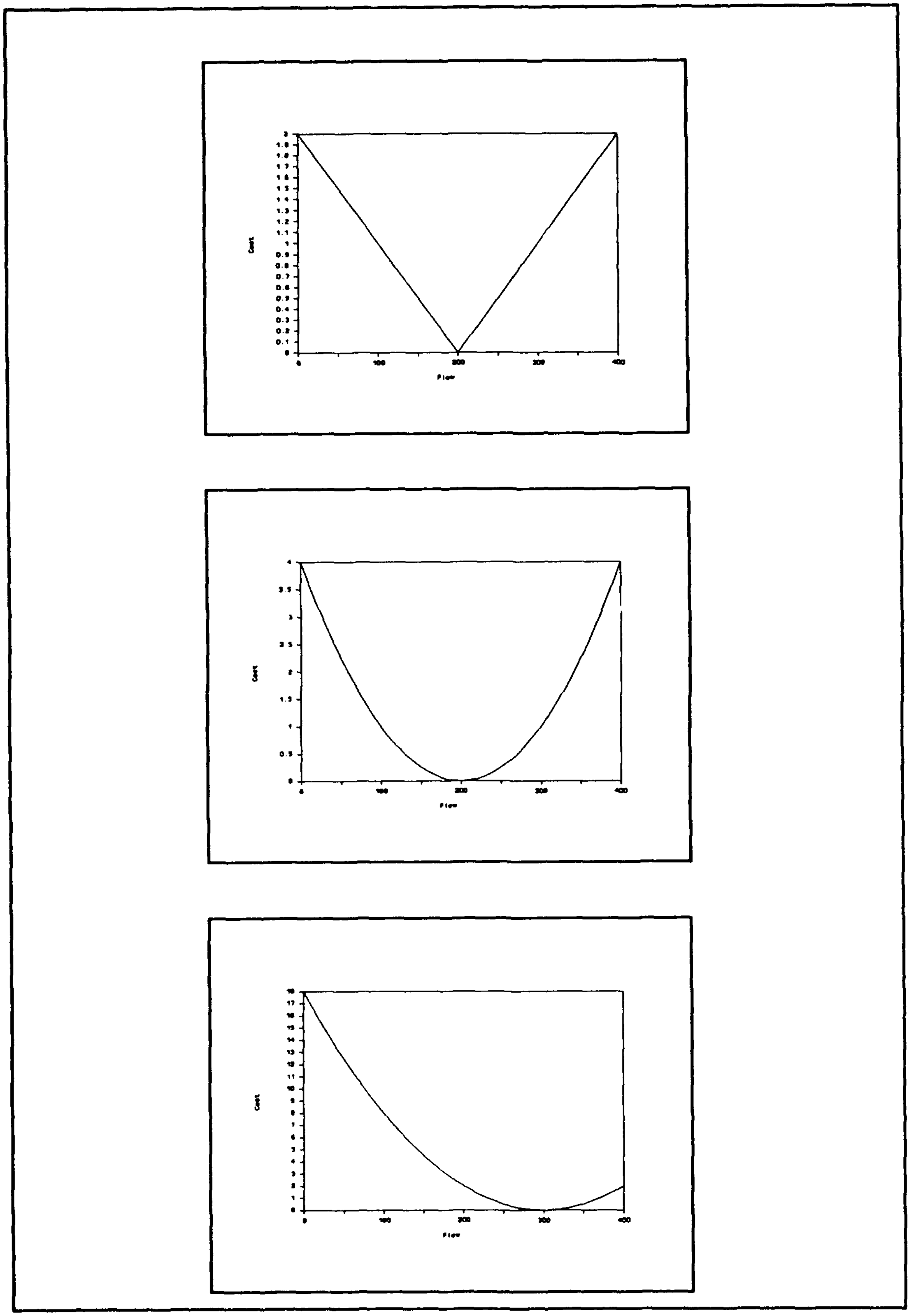

FIGURE C-4 Nonlinear Penalty Functions

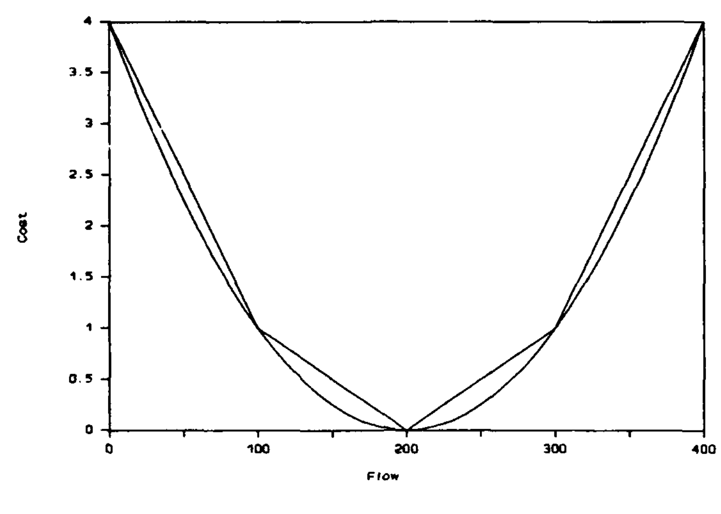

FIGURE C-5 Piecewise Linear Approximation of Nonlinear Penalty Function

With a piecewise linear approximation, the physical link for which the function applies is represented in the network by a set of parallel arcs. One arc is included for each linear segment of the piecewise approximation. For example, suppose the cost function in Figure C-5 represents the cost of release from the reservoir represented by node 3 in Figure C-1. In the proposed network model, four parallel arcs will connect node 3 to node 4. Characteristics of the arcs are shown on Table C-1.

TABLE C-1
Example Network Model Arc Characteristics

Arc Number (1)	Lower Bound (2)	Upper Bound (3)	Unit Cost (4)
1	0	100	(1-4)/100=-0.03
2	0	200-100=100	(0-1)/100=-0.01
3	0	300-200=100	(1-0)/100= 0.01
4	0	400-300=100	(4-1)/100= 0.03

Arc 1 has the least marginal cost. Therefore, as flow is increased from node 3 to node 4, flow will pass first through arc 1. When the capacity of this arc is reached, flow begins to pass through arc 2. Arc 3 will have non-zero flow if and only if arc 2 is at its upper bound. Finally, arc 4 will have non-zero flow only when arcs 1, 2, and 3 are flowing full. Because the objective is to minimize cost, if two or more arcs are parallel, the one with the lowest unit cost is used first.

Develop Objective Function Representing Desirable Operation

Penalty Functions. All goals of system operation cannot be represented adequately with economic costs. Some of the goals are socially, environmentally, or politically motivated. Consequently, the objective function for the proposed model is formed from penalty functions, rather than cost functions. These penalty functions are in commensurate units, but those units are not necessarily dollars. The penalty functions represent instead the relative economic, social, environmental, and political penalties associated with failure to meet operation goals. Thus, even if failure to meet, for example, an environmental operation goal has no measurable economic cost, the penalty may be great.

Flow Penalty Functions. All operation goals related to reservoir-release, channel-flow, or diversion-flow flow are expressed with flow penalty functions. These functions may represent operation goals for navigation, water supply, flood control, or environmental protection.

Figure C-6 is an example of a flow penalty function. This function represents the relative penalty for diverting flow when the minimum desired diversion is 100 cfs. Less diversion is undesirable. More diversion is acceptable, but that water does not reduce further the penalty.

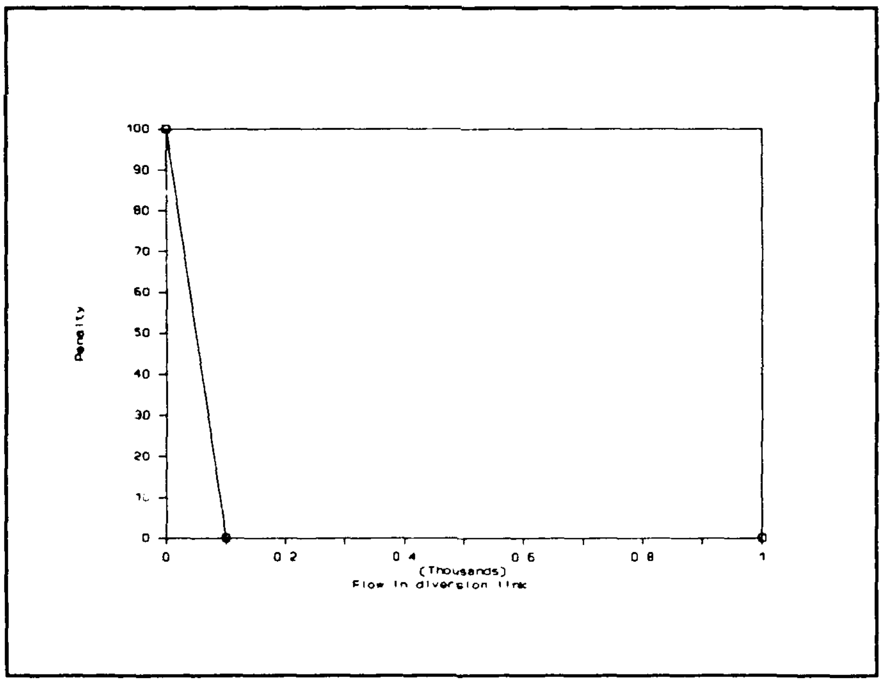

FIGURE C-6 Typical Flow Penalty Function

The penalty function of Figure C-6 is represented in the network by two parallel arcs. The characteristics of these arcs are shown on Table C-2.

TABLE C-2
Penalty Function Arc Parameters

Arc Number (1)	Lower Bound (2)	Upper Bound (3)	Unit Cost (4)
1	0	100	(0-100)/100=-1.00
2	0	1000-100=900	0.00

The first arc represents flow up to the desired rate. As the flow increases from 0 cfs to 100 cfs, the total penalty decreases. At 100 cfs, the unit penalty is 0.00. As the flow increases beyond 100 cfs, the unit penalty remains 0.00.

Similar penalty functions can be developed for reservoir release and channel flow.

Storage Penalty Functions. All reservoir operation goals uniquely related to storage are expressed through penalty functions for arcs that represent reservoir-storage. These functions may represent operation goals for reservoir recreation, water supply, or flood control.

Figure C-7 is an example of a reservoir storage penalty function. For this example, the top of the permanent pool is 200 kaf, the top of the conservation pool is 800 kaf, and the top of the flood-control pool is 1000 kaf. The function represents penalty for storage when the reservoir operation goal is to keep the inactive and conservation pools full and the flood control pool empty.

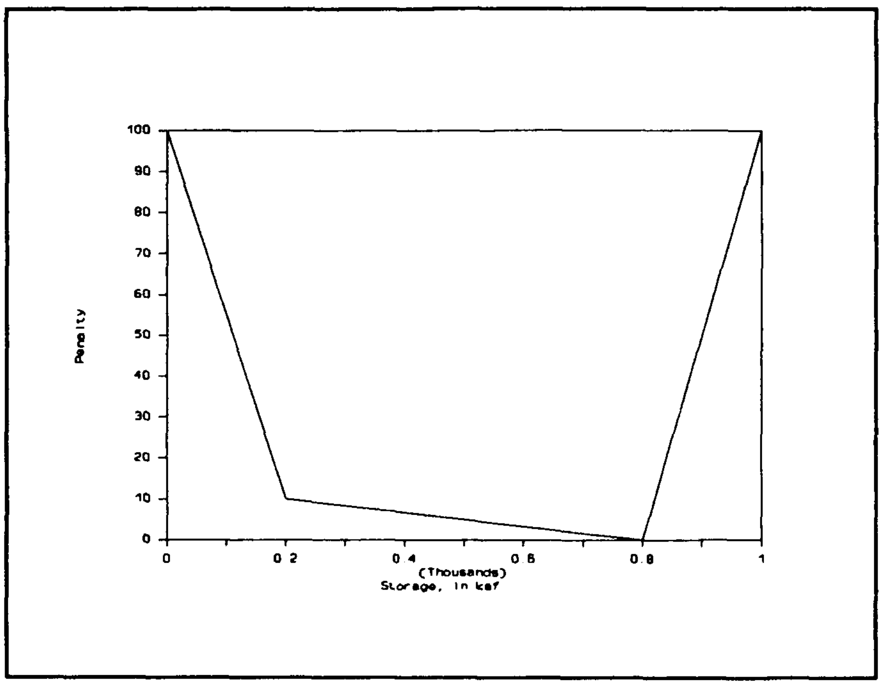

FIGURE C-7 Typical Storage Penalty Function

The function of Figure C-7 is represented in the network by three parallel arcs. The flow along one arc represents storage in the permanent pool. Increasing the flow along this arc reduces the penalty rapidly. Flow along the second arc represents storage in the conservation pool. Increasing flow along this arc also decreases the penalty, but not as rapidly as does flow along the inactive-pool arc. The third arc represents storage in the flood-control pool. Increasing flow along the flood-control pool arc increases the penalty. The solver will allocate flow to the arcs to minimize the total system penalty: first to the inactive-pool arc, then to the conservation-pool arc, and finally to the flood-control pool arc.

Storage and Flow Penalty Functions. Certain system operation goals depend on both storage and flow. The most significant is hydroelectric energy generated at a reservoir. This is a function of the product of release and head on the turbine. Head is the difference in reservoir-surface elevation and downstream water-surface elevation. Reservoir-surface elevation is a function of reservoir storage, and downstream water-surface elevation is a function of release. Thus, the energy generated is a complex function of storage and flow.

Figure C-8 illustrates a typical energy penalty function. Here, penalty is measured in terms of reduction in value of the energy produced, when compared to the firm energy target. Additional energy generated has a value, but that value is less that firm energy. Thus the slope is less.

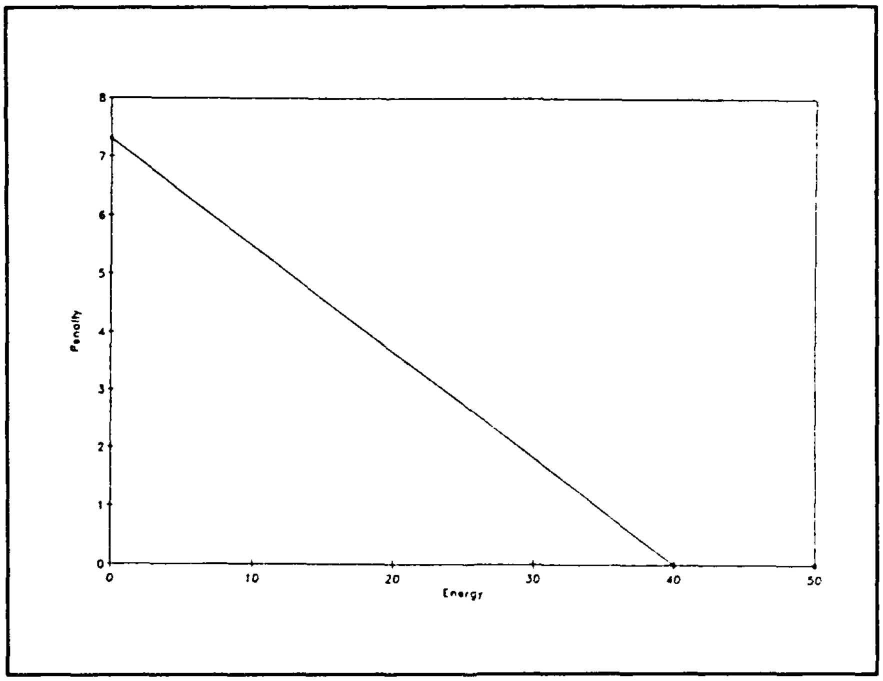

FIGURE C-8 Typical Hydropower Penalty Function

Solve the Network Problem with an Off-the-shelf Solver

Mathematical Statement of Problem. The optimization problem represented by the network with costs associated with flow can be written as follows (Jensen and Barnes, 1980):

$$\text{Minimize:} \quad \sum_{k} h_k f_k \tag{1}$$

subject to

$$\sum_{k \in M_O} f_k - \sum_{k \in M_T} a_k f_k = 0 \quad \text{(for all nodes)} \tag{2}$$

$$l_k \le f_k \le u_k \quad \text{(for all arcs)} \tag{3}$$

in which:

m = total number of network arcs;
h_k = unit cost for flow along arc k;
f_k = flow along arc k;
M_O = the set of all arcs originating at a node;
M_T = the set of all arcs terminating at a node;
a_k = multiplier for arc k;
l_k = lower bound on flow along arc k; and
u_k = upper bound on flow along arc k.

Equations 1, 2, and 3 represent a special class of linear-programming (LP) problem: the *generalized minimum-cost network-flow problem*. Solution of the problem will yield an optimal allocation of flow within the system.

Network Solvers. Jensen and Barnes (1980) describe a variety of solutions to the generalized minimum-cost and other network-flow programming problems. One solution is the flow-augmentation algorithm developed by Jensen and Bhaumik (1974). This algorithm determines the minimum-penalty flow in a generalized network by iteratively performing two computations. In the first computation, at the first iteration, the algorithm solves a shortest-path problem. That is, it determines a set of arcs that provide the minimum-penalty path from the source node to the sink node. In each successive iteration, the shortest-path computation deletes an arc with flow at upper bound from the path. It then adds the most promising available arc to create a new path. The second computation determines the maximum flow that can be directed from source to sink through the current shortest path. It increases flows in the arcs to achieve the maximum possible flow at the sink. If this flow equals an analyst-specified flow requirement at the sink, the algorithm terminates. Otherwise, the algorithm continues with the first computation. FORTRAN routines implementing this algorithm were published by Jensen and Bhaumik and used by Martin (1982). These routines are available at HEC.

If a_k = 1.00 for all k in Equation 2, the resulting problem is a *pure network-flow programming problem*. For this class of problem, faster solution algorithms are available. The well-known out-of-kilter (OKA) algorithm (Fulkerson, 1961) solves this pure network problem. A FORTRAN routine implementing the OKA has been available as shareware since 1967 (SHARE). Barr, Glover, and Klingman (1974) presented an improved formulation of the OKA and developed a FORTRAN code to implement their algorithm. They present results showing that the reformulated algorithm is faster than the share routine by a factor of 4 to 15 on large problems. This code, designated SUPERK, is published by the Texas Department of Water Resources (1975) and used by the California Department of Water Resources (Chung, et al., 1989). FORTRAN code for SUPERK is available at HEC.

Karney and Klingman (1976) present a special-purpose in-core, out-of-core code for solving capacitated transhipment and transportation network problems. They report that this code has solved problems with 50,000 nodes and 62 million arcs on a UNIVAC 1108 for the U.S. Treasury Department. They also report solution of networks with 625,000 arcs on machines with less than 30,000 words of central memory. This code, designated I/O PNET-I, is available commercially.

Post-process Network Results

The optimal allocation of water in the layered network is determined with a network solver. The solver finds the flow along each network arc that yields the total minimum-penalty circulation for the entire network, subject to the continuity and capacity constraints. These flows must be translated into reservoir releases, hydropower generation, storage volumes, diversion rates, and channel flows to be useful to the reservoir system operators.

For convenience, the results after translation will be stored with the HEC data storage system (HECDSS). Then the results can be displayed or processed further as needed to provide information required for decision making.

MODEL-BUILDING SOFTWARE

To the extent possible, the software to implement the network model will be general-purpose software. With this software, an analyst will be able to define the layout of any existing or proposed reservoir system. Further, the analyst will be able to describe the physical features of the system reservoirs and channels and the goals of and constraints on their operation. The operation goals will be defined by penalty functions associated with flow, storage, or both.

To permit representation of any reservoir system as a network, the software will include the following model-building components:

1. Inflow link;
2. Diversion link;
3. Channel-flow link;
4. Simple reservoir-release link;
5. Hydropower reservoir-release link;
6. Reservoir-storage link;
7. Initial-storage link;
8. Final-storage link; and
9. Nodes at which links are connected.

By selecting the appropriate links and the manner in which they are interconnected, the analyst can describe any system. By describing the characteristics of the links and the penalties associated with flow along the links, the analyst can define operating constraints and goals.

Inflow Link

An inflow link brings flow into the reservoir-system network. It originates at the source node and terminates at any other system node. In Figure C-1, the link from node 1 to node 3 is an inflow link. It originates at the source node, node 1, and carries flow into the system at node 3.

The flow along the arc representing the inflow link is an input to the model. This known inflow may be an observed inflow from the historical record, or it may be an inflow from a sequence generated with a statistical model. To insure that the link carries the specified flow, the arc upper and lower bounds are equal, and the unit penalty is zero.

Initial-storage Link

An initial-storage link is a special case of an inflow link. It originates at the source node and terminates at a node that represents a reservoir in the first period of analysis only. It introduces to the network the volume of water initially stored in the reservoir. In Figure C-2, the storage link terminating at node 3 in period 1 is an initial-storage link; it represents the beginning-of-period 1 storage.

As an initial-storage link carries a specified flow, no decision is represented by this link. To insure that the link carries the specified flow, the arc upper and lower bounds are equal, and the unit penalty is zero.

Diversion Link

A diversion link carries flow out of the system. It originates at any system node and terminates at the sink node. In Figure C-1, the arc from node 4 to node 2 is a diversion link. It originates in the system at the downstream control point, node 4. It carries flow out of the system to the sink, node 2.

The flow along a diversion link is a decision variable, selected to minimize total system penalty. The diversion penalty function is specified by the analyst as a convex piecewise approximation of the true penalty associated with deviating from the diversion desired. This function may vary by month. The software will define appropriate arc bounds and unit costs to represent the function.

The analyst may specify also inviolable minimum and/or maximum flow for a diversion link. If the analyst specifies both minimum and maximum, and if these values are the same, the diversion link will be represented in the network by a single arc. The upper and lower bounds of the arc are equal. In that case, the only feasible solution is one in which flow equals the specified value, regardless of cost. Any penalty function defined by the analyst for the link is ignored in that case, as it has no impact on the solution.

If the analyst specifies only a lower bound or only an upper bound, the software will impose the bound on the appropriate network arcs. If the penalty function is a simple function, like that of Figure C-3, the bound is applied to the single arc representing that function. For example, if the analyst specified a lower bound of 25 cfs and an upper bound of 800 cfs, the network arc will have $l_k = 25$ and $u_k = 800$ (see Equation 3).

For more complex penalty functions, the software must include an algorithm to determine the proper network arcs on which to impose the bound. For example, the penalty function of Figure C-6 is represented by two parallel arcs, with bounds and cost. If the analyst specifies an inviolable lower bound of 25 cfs and an upper bound of 800 cfs, the network arcs must be adjusted to have parameters shown on Table C-3.

TABLE C-3
Diversion Link Arc Characteristics

Arc Number (1)	Lower Bound (2)	Upper Bound (3)	Unit Cost (4)
1	25	100	-1.00
2	0	800-100=700	0.00

For the first arc, the lower bound increases from 0 to 25. The upper bound remains 100. The unit cost does not change. For the second arc, the lower bound remains 0, and the upper bound now is 800 - 100 = 700. The unit cost does not change.

Final-storage Link

A final-storage link is a special case of a diversion link. It carries flow out of the system, but only from a reservoir in the last period of analysis. The final storage link thus originates at any system reservoir and terminates at the sink node. In Figure C-2, the storage link originating at node 3 in period 3 is a final-storage link. The final-storage link is included in the system model to permit assignment of a future value for water in system reservoirs. Otherwise, the network solver will be indifferent regarding final storage. The solver may chose any storage state, including empty or full, without regard for future use.

Just as with the diversion link, the flow along a final-storage link is a decision variable, selected to minimize total system penalty. The penalty function is specified by the analyst as a convex piecewise approximation of the true penalty associated with deviating from the an ideal final storage. The software will define appropriate arc bounds and unit costs to represent this function.

As with the diversion link, the analyst may specify also inviolable minimum and/or maximum storage for a final-storage link. The software will impose these constraints on the appropriate network arcs.

Channel-flow Link

A channel-flow link originates at any non-reservoir node, terminates at any other network node, and represents the flow in a channel reach. The flow along the link is a decision variable, selected to minimize total system penalty.

As with the diversion link, the analyst may specify inviolable minimum and/or maximum flow for a channel-flow link. The software will impose these constraints on the appropriate network arcs.

The analyst may specify also a multiplier for flow along a channel-flow link. The multiplier is a_k of Equation 2 for all arcs representing the link. If the multiplier is greater than 1.00, it represents increase of flow in the channel. If the multiplier is less than 1.00, it represents loss of flow.

Simple Reservoir-release Link

The reservoir-release link originates only at a non-hydropower reservoir node, terminates at any other node, and represents the total outflow from a reservoir. This includes release and spill. The flow along a reservoir-outflow link is a decision variable, selected to minimize total system penalty. In Figure C-1, the link from node 3 to node 4 is a simple reservoir-release link. It originates at a node representing a reservoir and terminates, in this case, at a node representing a demand point.

The analyst may specify inviolable minimum and/or maximum flow constraints. The analyst may specify also a multiplier for flow along a reservoir-release link. The software will apply the multiplier and impose the constraints on the appropriate network arcs.

Hydropower Reservoir-release Link

Link Description. A hydropower reservoir-release link (hydro-release link) originates only at a hydropower reservoir node, terminates at any other node, and represents the total outflow from the reservoir. This includes release and spill.

The flow along a hydro-release link is a decision variable, selected to minimize total system penalty. As hydroelectric energy is not a linear function of flow, however, determination of the release that minimizes total penalty requires consideration of storage.

Hydropower Computation From Link Flow. The nonlinear hydro-release problem will be solved via iterative solution of linear approximations. Such successive linear programming techniques are described by Martin (1982), Grygier and Stedinger (1985), and Reznicek and Simonovic (1990). In summary, these techniques convert the energy penalty functions to release penalty functions by assuming a value of reservoir storage. Given the storage, head can be estimated. Given this head, the unit penalty for release is used, and the flow allocation problem is solved. Then the head assumption is checked, using the storage computed for the optimal allocation. If the assumption is not acceptable, the heads corresponding to the computed storages are used, and the process is repeated.

The algorithm proposed by Grygier and Stedinger (1985) will be employed in the proposed model. This algorithm solves the hydro-release problem as follows:

1. Set ITER, an iteration counter, equal zero. Assign a value to ΔS_{max}, the maximum allowable storage deviation.

2. For each hydro-release link for each period, estimate the beginning-of-period (BOP) and end-of-period (EOP) storage for penalty calculation. Note that this may be a reservoir other than that upstream of the link.

3. Determine the BOP and EOP head corresponding to the storage. Given the head, convert the energy penalty function to a flow penalty function. Assign the appropriate linear costs and bounds to the release arcs. Add constraints to the storage arcs so the storage does not vary by more than ΔS_{max}.

4. Solve the resulting network flow programming problem.

5. For each hydro-release link for each period, determine the average storage with the optimal network solution. Compare the computed values with the values used in step 2. If all values are accurate within a user-specified tolerance, stop. Otherwise, go to step 6.

6. If the objective function value is worse than the value found in the previous iteration, go to step 7. Otherwise, accept this solution. Determine from the optimal solution the BOP and EOP storage for each hydro-release link for each period. Set ITER = ITER + 1 and decrease ΔS_{max}. Repeat the computations, beginning with step 2.

7. Decrease ΔS_{max}. Repeat the computations, beginning with step 3, without updating the storage estimates.

Other Release Penalties. Due to the special nature of the hydro-release link, all other release-related penalties must be defined as a function of flow downstream. This is accomplished by defining a "dummy" node downstream of the hydropower reservoir. The hydro-release link connects the reservoir and this dummy node, and the hydropower penalty function is associated with this link. A channel-flow link connects the dummy node with the next downstream node. All penalty functions normally defined in terms of reservoir release are defined in terms of channel flow instead.

Reservoir-storage Link

Link Description. A reservoir-storage link originates at any reservoir node in a layered, multiple-period network. It represents the volume of water stored in the reservoir at the end of the period. The reservoir-storage link terminates at the node representing the same reservoir in the period following. The flow along a reservoir-storage link is a decision variable, selected to minimize total system penalty.

For example, in Figure C-2, the arc from node 3 in period 1 to node 3 in period 2 is a reservoir-storage link. Flow along the arc leaving the period-1 layer represents reservoir storage at the end of period 1. Flow along the arc entering the period 2 layer represents reservoir storage at the beginning of period 2.

Evaporation Computation With Link Flow. To approximate reservoir evaporation, a fraction of flow entering the reservoir-storage link may be "lost". For the network model, the relationship of storage and evaporation is given by

$$S_t = S_{t-1} - EV_{t-1} \tag{4}$$

in which:

S_t = reservoir storage at beginning of period t;
S_{t-1} = reservoir storage at end of period t-1;
EV_{t-1} = volume of reservoir evaporation. The evaporation volume is related to reservoir surface area with the following equation:

$$EV_{t-1} = (ED_{t-1})\,(A_{t-1}) \tag{5}$$

in which:

ED_{t-1} = evaporation rate in period t-1; and
A_{t-1} = reservoir surface area in period t-1.

The quantity ED_{t-1} is input to the model. It may be an historically observed evaporation rate, or it may be generated with a statistical model. The relationship of surface area and storage can be approximated with a linear function as

$$A_{t-1} = \beta\, S_{t-1} \tag{6}$$

in which: β = a linear coefficient. The value of β is found from analysis of specified reservoir characteristics. Substituting Equations 5 and 6 into Equation 4 and simplifying yields

$$S_t = (1 - ED_{t-1}\,\beta)\,(S_{t-1}) \tag{7}$$

The quantity $(1 - ED_{t-1}\,\beta)$ is an arc multiplier. The flow out of the reservoir-storage arc, S_t, is the flow into the arc, S_{t-1}, multiplied by $(1 - ED_{t-1}\,\beta)$. This multiplier is the arc multiplier a_k of Equation 2.

If the magnitude of $(1 - ED_{t-1}\,\beta)$ is approximately 1.00 for all periods of analysis, S_t = S_{t-1}. That is, reservoir storage at beginning of period t = reservoir storage at end of period t-1. In that case, the network-flow programming is no longer a generalized network problem. Instead, it is a pure network problem. Faster solvers may be used.

Nodes

Nodes are included in the model to permit joining the appropriate links. Two or more of the links described may join at a node. The nodes represent system reservoirs, demand points, channel junctions, or diversion points. These may be existing facilities or proposed facilities. Additional nodes may be included in the network for convenience of description.

In addition to the analyst-defined nodes, the software will incorporate in the network a source node and a sink node to satisfy the mathematical requirements for defining a network. All water entering the system flows from the source node. All water leaving the system flows to the sink node. These hypothetical nodes have unlimited capacity.

TYPICAL PENALTY FUNCTIONS

The goals of reservoir system operation are identified by the analyst via penalty functions. The functions define, as a function of flow, storage, or both, the economic, social, and environmental cost for deviating from ideal operation for each of the system operation purposes. These purposes include flood control, navigation, lake and stream recreation, water supply, environmental protection, and hydropower.

Flood-control Penalty Function

A flood-control penalty function defines the cost of deviating from ideal flood-damage-reduction operation. This function typically will relate penalty to channel-link flow or reservoir release link flow.

Figure C-9 is a typical flood-control penalty function. In this example, no penalty is incurred for flows less that 600 cfs, the channel capacity. Between 600 cfs and 1100 cfs, the penalty is slight, increasing to 100 units. The penalty is much greater for flows exceeding 1100 cfs. This represents significant damage incurred as the flow moves out of the 10-25 year floodplain and into surrounding property.

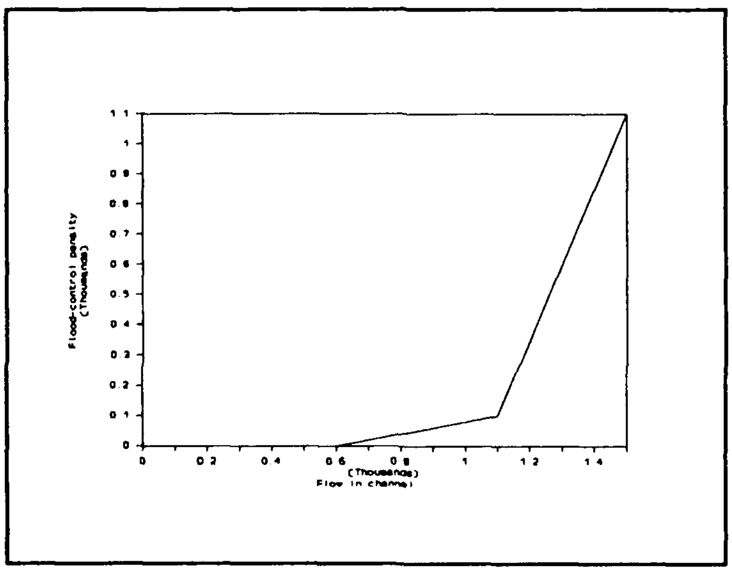

FIGURE C-9 Typical Flood-control Penalty Function

Navigation Penalty Function

A navigation penalty function defines the cost of deviating from flows desired for vessel traffic in a system channel.

Figure C-10 is a typical navigation penalty function. In this example, the penalty is great for flows less than 400 cfs; this represents the minimum desired flow for towing barges in the channel. Between 400 and 600 cfs, the penalty is zero, as this is the desired flow for navigation. Between 600 and 1100 cfs, the penalty increases slightly, representing the increased effort required for navigation. Finally, the penalty increases rapidly if the flow exceeds 1100 cfs. This is the upper limit on desired flow for navigation.

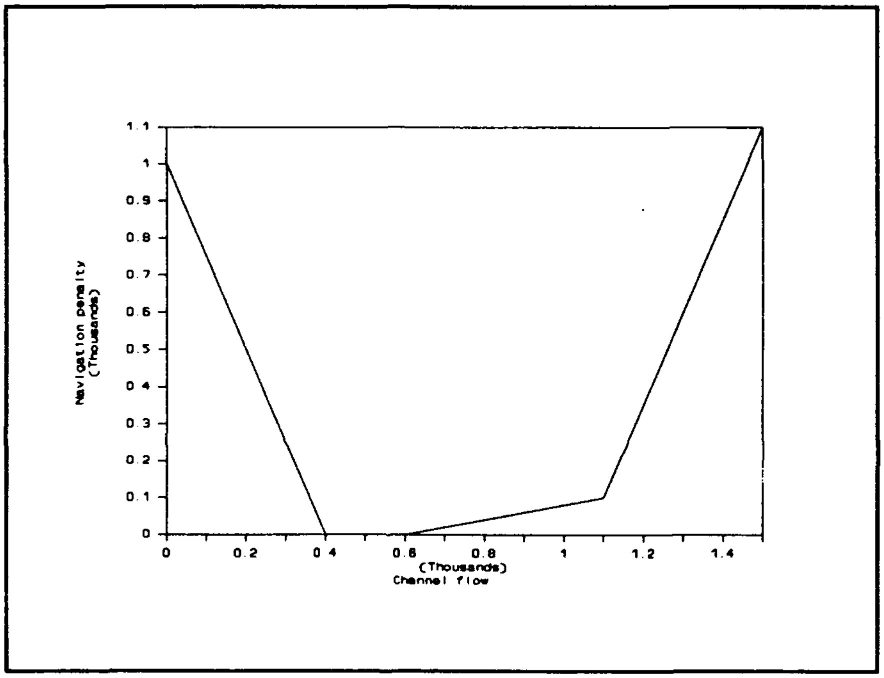

FIGURE C-10 Typical Navigation Penalty Function

Recreation Penalty Functions

A recreation penalty functions may represent the relationship of recreation to reservoir storage or channel flow. Figure C-11 is an example of a typical lake recreation function. In this example, the desired range of active storage for recreation is 40 to 80 kaf. If the reservoir storage is less than 40 kaf, the boat ramps are inaccessible, and recreation is hazardous. If the reservoir storage is more than 80 kaf, the reservoir is in flood operation, and recreation is hazardous. Consequently, the function is shaped as shown.

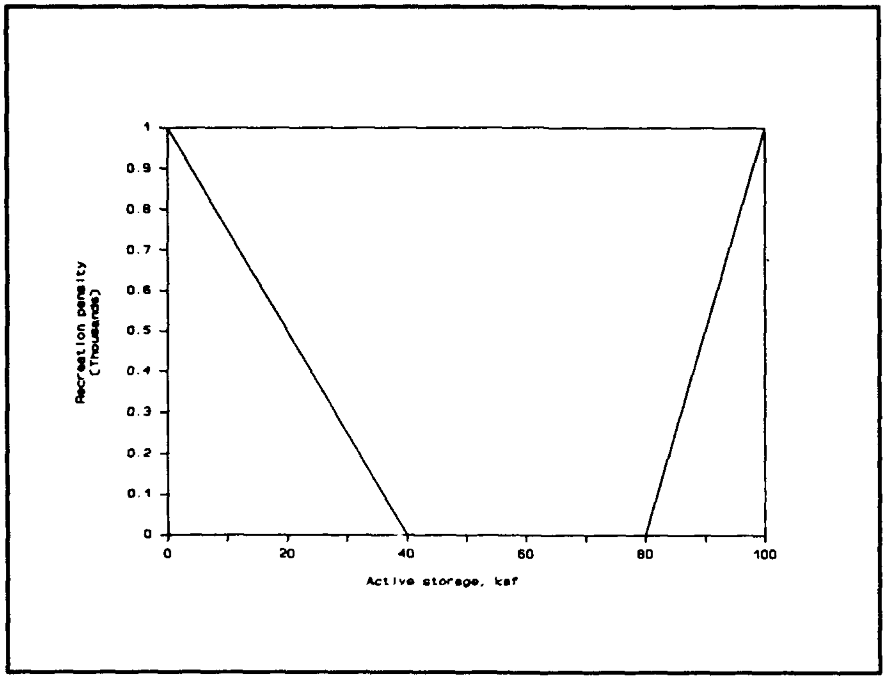

FIGURE C-11 Typical Lake Recreation Penalty Function

Figure C-12 is a typical river recreation penalty function. In this example, the desired range of flow for boating, swimming, and fishing is 400 to 500 cfs. If the flow rate is less than 400 cfs, boating and swimming are dangerous due to shallow depths and fishing is poor. If the flow rate exceeds 500 cfs, recreation is hazardous.

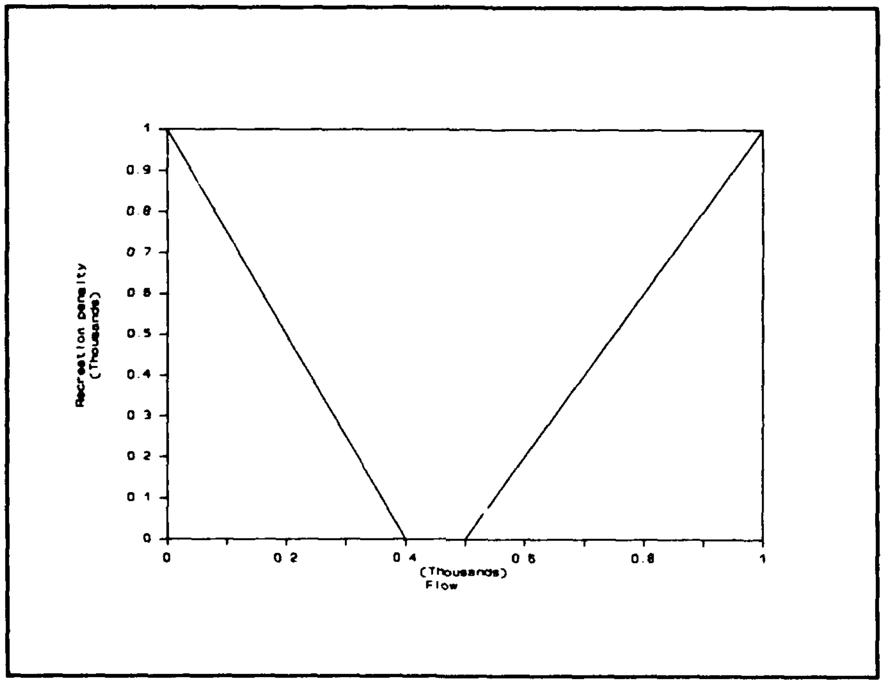

FIGURE C-12 Typical River Recreation Penalty Function

Water-supply Penalty Function

A water-supply penalty function describes desired operation for supply of water for municipal and industrial use or for irrigation. A water-supply penalty function may relate to channel-link flow, simple reservoir-release flow, or diversion flow. Figure C-13 is a typical water-supply penalty function. In this function, the desired flow for water supply is 100 cfs. If the flow is less, demands are not met, so the penalty is great. If the flow exceeds the desired rate, the water is used, but the benefit is not great, as it is not dependable supply.

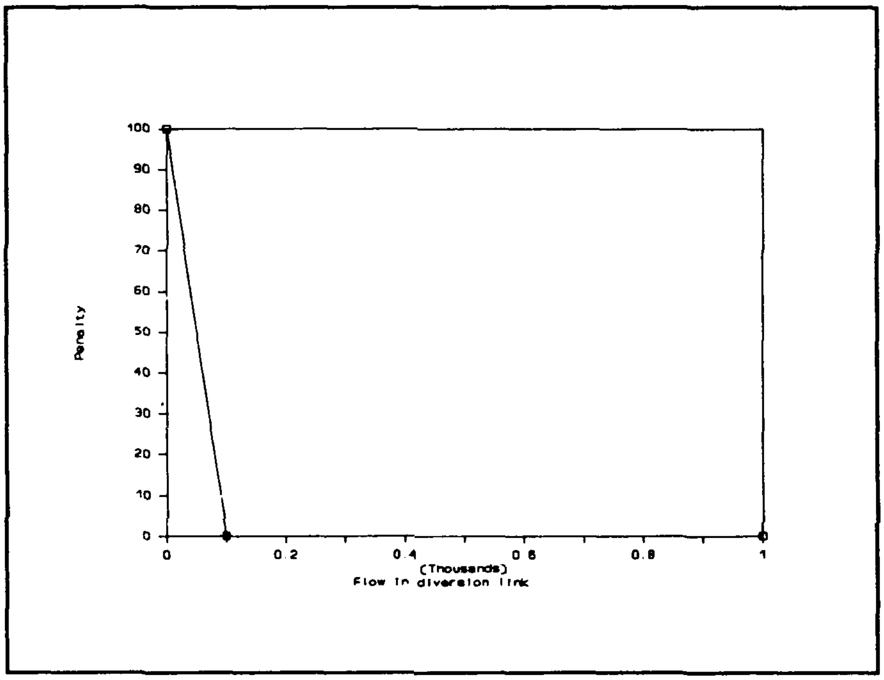

FIGURE C-13 Typical Water-supply Penalty Function

Environmental Penalty Function

An environmental penalty function represents the desired operation for environmental protection. The function may define penalty for flow or penalty for storage or penalty or both. A typical case is illustrated by Figure C-14. In this example, an average monthly flow of 100 cfs is required to preserve wildlife habitat. If the flow is less or more, the habitat is destroyed. In that case, only the desired value is assigned zero penalty. For all other flows, the penalty is positive.

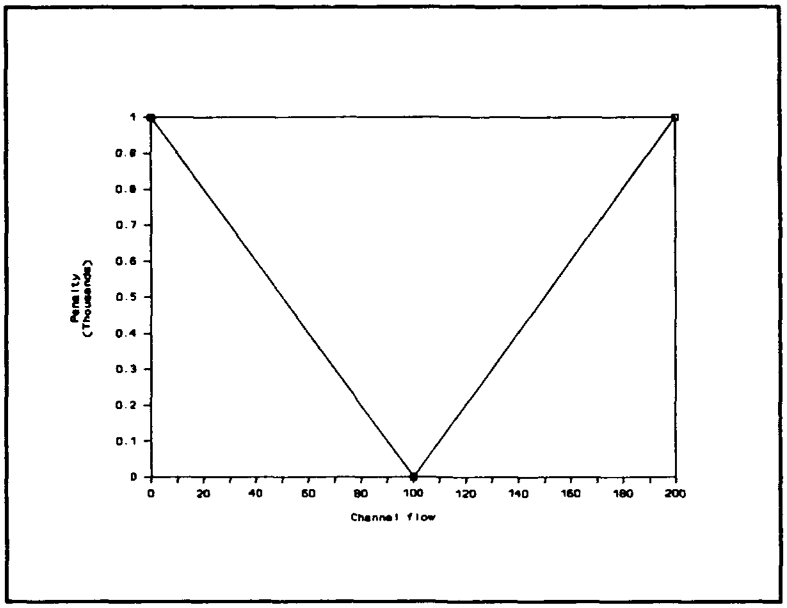

FIGURE C-14 Typical Environmental Penalty Function

Hydropower Penalty Function

A hydropower penalty function is assigned to a hydro-release link only and defines the cost of deviation from desired system operation for energy production. For the proposed model, Figure C-15 illustrates the acceptable form of the function. This function defines penalty as a function of release for a specified head (storage). If the head is less than the optimal head for the generator, the penalty is positive. Likewise, if the release is less than optimal for a specified head, the penalty is positive.

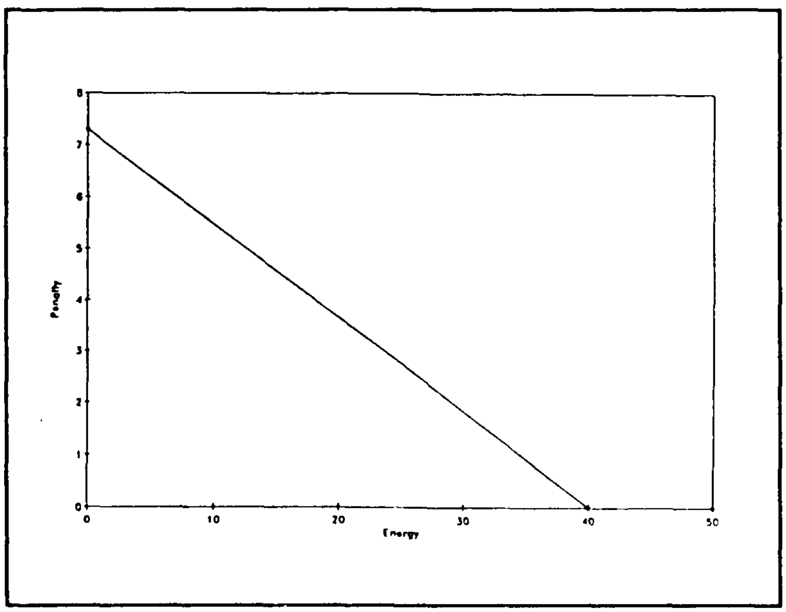

FIGURE C-15 Typical Hydropower Penalty Function

Combined Penalty Functions

If two or more penalty functions apply to a single stream reach or to a single reservoir, the functions are combined to yield a single penalty function. The combined penalty function then is used in the optimization. For example, a reservoir hydropower capacity penalty function, a reservoir recreation penalty function, and a water supply reservoir penalty function may apply for a reservoir. To combine the functions, the various penalties for a given storage are added. The resulting function is then edited or smoothed to yield a convex function. This convex function then is represented in a piecewise linear fashion for the network. Figure C-16 illustrates this.

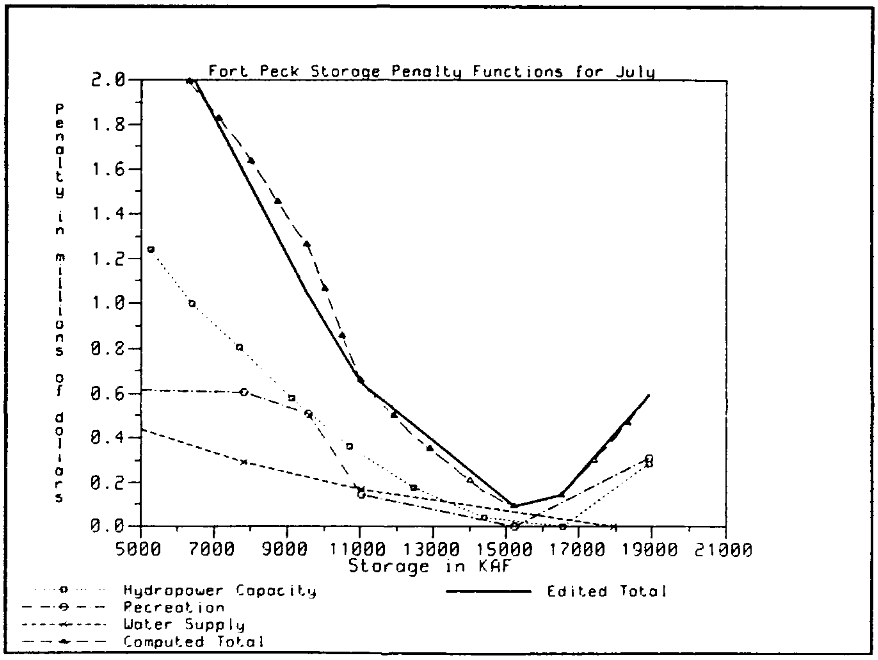

FIGURE C-16 Penalty Functions Combined

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GLOSSARY

arc Connects two nodes of a network. In network-flow programming, each arc has three parameters: a lower bound, which is the minimal amount that can flow along the arc; an upper bound, which is the maximum amount that can flow along the arc; and a cost for each unit that flows along the arc.

channel-flow link Represents the flow in a channel reach. A channel-flow link originates at any non-reservoir node and terminates at any network node.

constraint Limit the decision variables to their feasible or permissible values.

convex function A function $f(X)$ for which the following is true for any two distinct points X_1 and X_2 and for $0<\lambda<1$: $f(\lambda X_1+(1-\lambda)X_2) < \lambda f(X_1)+(1-\lambda)f(X_2)$

decision variable The unknowns which are to be determined from the solution of the model.

diversion link Carries flow out of the system. A diversion link originates at any system node and terminates at the sink node.

final-storage link Carries flow out of the system, but only from a reservoir in the last period of analysis. It originates at a reservoir node and terminates at the sink node.

hydropower reservoir-release link Represents the release from a hydropower reservoir. The penalty function for a hydropower reservoir-release link depends on both the release from the reservoir and the storage in the reservoir.

inflow link Brings flow into the reservoir-system network. An inflow link originates at the source node and terminates at any system node.

initial-storage link Introduces to the network the volume of water initially stored in a system reservoir. The initial-storage link originates at the source node and terminates at a reservoir node in the first period of analysis only.

network A collection of arcs and nodes.

network-flow programming An optimization procedure for allocating flow along the arcs of a network. Network-flow programming is a special class of linear programming.

node The junction of two or more network arcs. The node may represent a system reservoir, demand point, channel junction, diversion point. The sum of flow in arcs originating at a node equals the sum of flow in all arcs terminating at the node.

objective function Defines the overall effectiveness of a system as a mathematical function of its decision variables. The optimal solution to the model yields the best value of the objective function, while satisfying all constraints.

penalty function Defines the penalty for less-than-perfect operation as a function of flow, storage, or both.

piecewise linear approximation Is an approximation in which a non-linear function is represented by linear segments, arranged sequentially.

reservoir-storage link Represents the volume of water stored in a reservoir at the end of a period. The link originates at any reservoir in a layered, multiple-period network and terminates at the node representing the same reservoir in the period following.

simple reservoir-release link Represents the total outflow from a non-hydropower reservoir. Flow in the link includes release and spill.

sink node Is the hypothetical absorber of all flow in the network. All diversion links and final-storage links terminate at the sink node.

solver Finds the minimum-cost allocation of flow to the network arcs, subject to the upper and lower bounds on arc flows and to continuity at the network nodes.

source node Is the hypothetical provider of all flow in the network. All inflow links and initial-storage links originate at the source node. No user-defined links terminate at the source node.

APPENDIX D

MISSOURI RIVER NETWORK MODEL DESCRIPTION

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MISSOURI RIVER NETWORK MODEL DESCRIPTION

MISSOURI RIVER SYSTEM DESCRIPTION

The Missouri River main-stem reservoir system consists of six reservoirs: Ft. Peck, Garrison, Oahe, Big Bend, Ft. Randall, and Gavins Point. These reservoirs and the area they service are shown in Figure D-1.

According to the reservoir regulation master manual (USACE, 1979), the main stem system is operated "...for flood control, navigation, irrigation, power, water supply, water quality control, recreation, and fish and wildlife." Current operation priorities in operating the reservoirs tc meet these objectives are described as follows in the regulation manual (pg. IX-1, IX-2):

> *<u>First,</u> flood control will be provided for by observation of the requirement that an upper block of this intermediate storage space in each reservoir will be vacant at the beginning of each year's flood season...*
>
> *<u>Second,</u> all irrigation, and other upstream water uses for beneficial consumptive purposes ... will be allowed for. This allowance also covers the effects of upstream tributary reservoir operations ...*
>
> *<u>Third,</u> downstream M&I water supply and water quality requirements will be provided for.*
>
> *<u>Fourth,</u> the remaining water supply available will be regulated in such a manner that the outflow from the reservoir system at Gavins Point provides for equitable service to navigation and power.*
>
> *<u>Fifth,</u> ... the efficient generation of power to meet the area's needs ... will be provided for.*
>
> *<u>Sixth,</u> insofar as possible without serious interference with the foregoing functions, the reservoirs will be operated for maximum benefit to recreation, fish and wildlife.*

A review of these priorities was prompted by the following (USACE, 1990a):

> *1. It has been 10 years since the last update.*
>
> *2. The current (3 year) drought has pointed out that parts of the existing Master Water Control Manual may require change...*
>
> *3. Recreation on the reservoirs and the river downstream is becoming an increasingly important industry...*

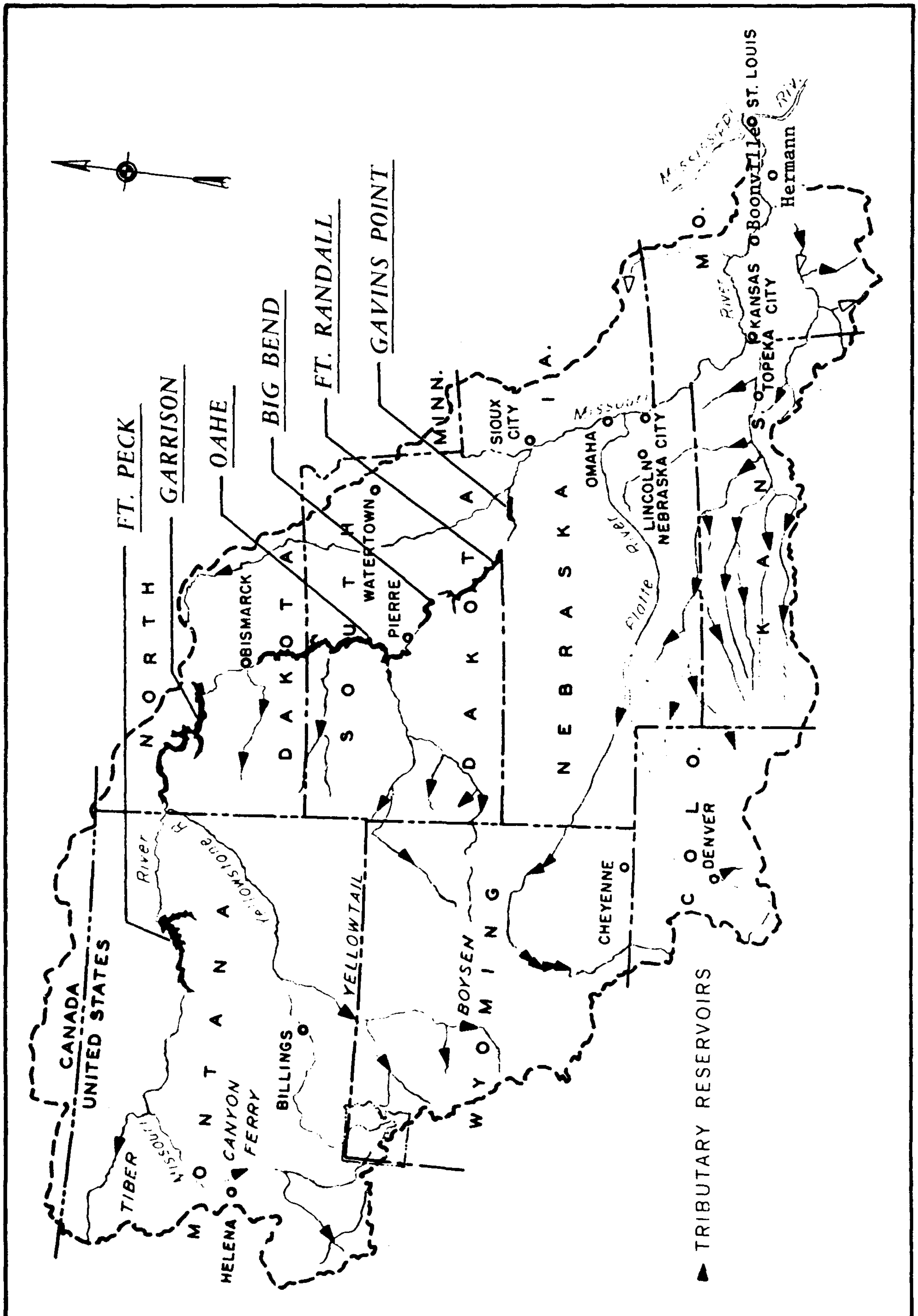


FIGURE D-1 Missouri River Reservoir System

4. The current drought has demonstrated the importance of Missouri River water to commercial navigation...

5. The Master Water Control Manual needs to be updated to include regulation criteria for endangered and threatened species, new data collection methods, and flood history which has occurred since the last update.

NETWORK REPRESENTATION

Summary

To provide quantitative information for the review, a prescriptive model of the system will be developed. The model will identify the water allocation that minimizes poor performance for all defined system purposes. Performance will be measured with analyst-provided penalty functions of flow or storage or both. The physical system will be represented as a network, and the allocation problem will be formulated as a minimum-cost network flow problem. The objective function of this network problem is the sum of convex, piecewise-linear approximations of the penalty functions.

Figure D-2 is a diagram of the network-model of the Missouri River system for the Phase I study. The system ends at Hermann, and thus does not consider Mississippi River supplies and demands. For analysis of multiple-period operation, this network is duplicated and layered, as described in *Requirements for a System Model of Missouri River Main Stem Reservoir System* (USACE, 1990b). In the proposed Phase I study, the network is duplicated 276 times to analyze monthly operation for the 23 year critical period resulting from the drought of the 1930's.

Network Nodes

The review of system priorities is divided into two phases. For Phase I of the study, the network representation includes six reservoir and six non-reservoir nodes. The reservoir nodes represent Ft. Peck, Garrison, Oahe, Big Bend, Ft. Randall, and Gavins Point. The non-reservoir nodes represent Sioux City, Omaha, Nebraska City, and Kansas City, Boonville, and Hermann. All network links either originate or terminate at one of these nodes.

Network Links

For Phase I of the study, the network representation includes the following links:

Inflow Links. An inflow link terminates each period at the Ft. Peck, Garrison, Oahe, Ft. Randall, and Gavins Point reservoir nodes. No inflow link is included for Big Bend reservoir. An inflow link terminates each period at all non-reservoir nodes. Thus, the network includes eleven inflow links per period. For the critical period analysis, the network includes 23 x 12 x 11 = 3036 inflow links. Each of these links is represented by a single network arc. The upper bound and lower bound of the arc equal the monthly inflow.

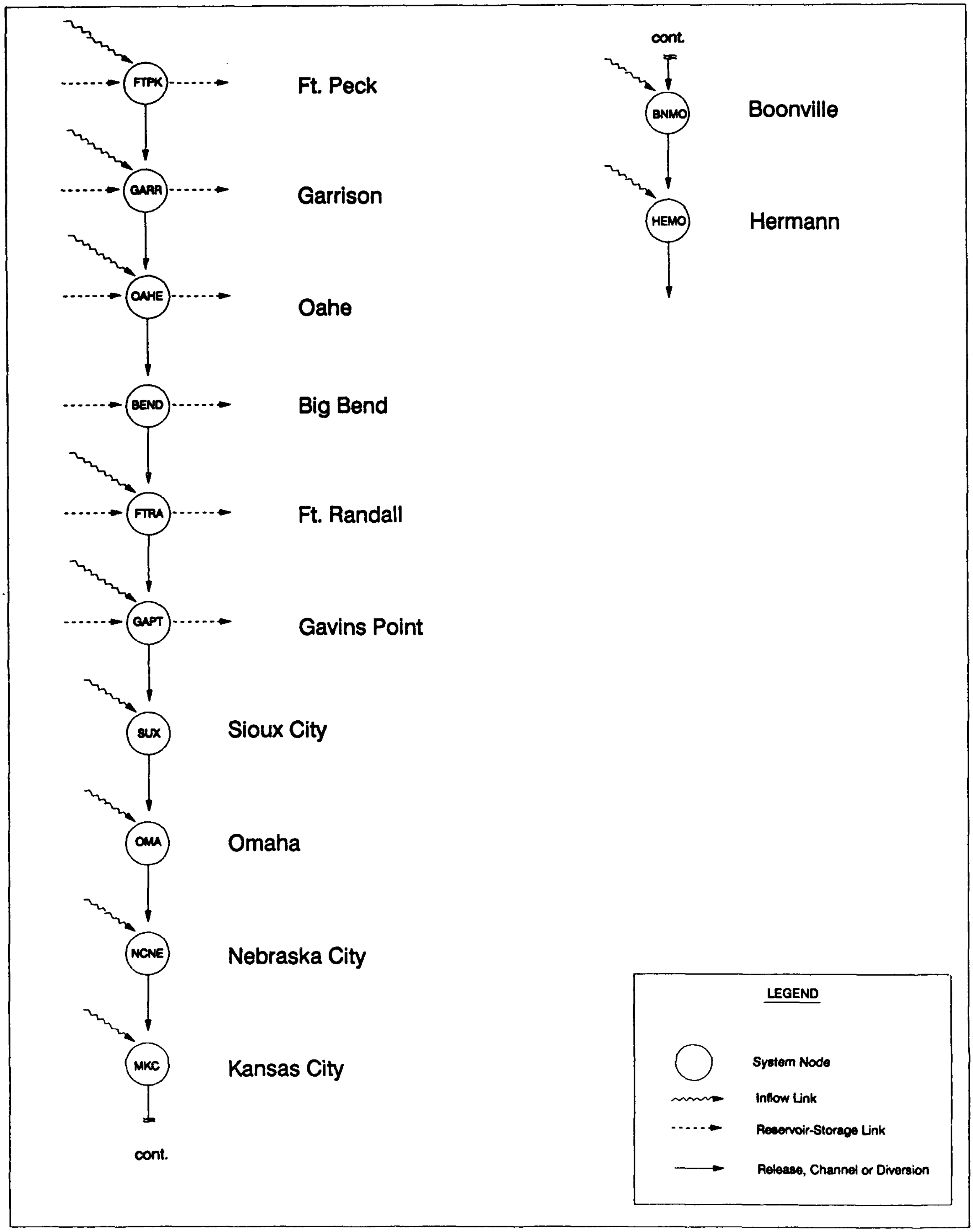


FIGURE D-2 Network Diagram of Missouri River Main Stem Reservoir System

Initial-storage Links. An initial-storage link terminates at each reservoir node in the first period of analysis. These links establish the initial storage for the analysis. For the Phase I analysis, the network includes six initial-storage links. Each of these links is represented by a single network arc. The upper bound and lower bound of the arc equal the desired initial storage.

Diversion Links. The network ends with a diversion link at Hermann City for each period. This link carries flow out of the network at its downstream end. The Phase I network includes 23 x 12 = 276 diversion links. Each link is represented by network arcs as necessary to model the penalty function for flow downstream of Kansas City.

Final-storage Links. A final storage link originates at each reservoir node in the final period of analysis. The network includes six final-storage links. As described in *Requirements for a System Model ...* (USACE, 1990b), a special penalty function should be specified for these links, and an upper and lower bound also may be specified. For the Phase I model, only the upper and lower bounds are implemented.

Channel-flow Links. Five channel-flow links connect the six non-reservoir nodes each period. For the 23-year critical period, the network includes 23 x 12 x 5 = 1380 channel-flow links. Each of these links is represented by network arcs necessary to model the penalty function.

Simple Reservoir-release Links. For the Phase I model, a reservoir-release links connects each reservoir node with the next downstream node each period. For all reservoirs except Gavins Point, this next downstream point is another reservoir. The node downstream of Gavins Point represents Sioux City. The critical-period network includes 23 x 12 x 6 = 1656 simple reservoir-release links.

For the Phase I analysis, all hydropower-release links are represented as simple reservoir-release links. This is accomplished by assuming a constant head at the reservoir. Energy penalty functions can then be expressed as release penalty functions. This assumption eliminates the need for iteration solution of the hydropower-release problem.

Reservoir-storage Links. Storage in each reservoir each period is represented with a reservoir-storage link. Each of these storage links has an amplification factor to represent lake evaporation as a linear function of storage. The network includes (23 x 12 - 1) x 6 = 1650 reservoir-storage links plus six links in place of the final storage links. Each link is represented in the network by arcs necessary to model the storage penalty functions.

SYSTEM DATA

Reservoir-inflow and Local-flow Data

Reservoir-inflow and local-flow data are provided by the Missouri River Division (MRD), USACE, in computer-readable form. Flows are provided for all reservoirs except Big Bend and for the six downstream nodes. The flow data are in units of 1000 acre-feet per month. These data are included as Exhibit D-1 of this Appendix. MRD developed the inflow data using historic stage and discharge records. Some of the data were recorded

daily and some were recorded continuously. Streamflow measurements at the present stations on the main-stem of the river were started in 1928.

Reservoir-inflow and Local-flow Depletions

According to MRD, the reservoir-inflow and local-flow data must be adjusted to account for depletions. Depletions include irrigation diversions, evaporation from major impoundments other than the six main-stem reservoirs, fish and wildlife use, land treatment, minor impoundments, rural domestic water supply, municipal and industrial water supply, and forestry use (USACE, 1979, pg. III-16). The MRD has provided a machine-readable record of historical depletions. The depletions are in units of 1000 acre-feet per month. A negative depletion indicates water was removed from the system whereas a positive depletion indicates water was added to the system. These data are included as Exhibit D-2 of this Appendix. Water use for all purposes has expanded significantly during the study period. The depletions are adjusted to represent a common level of water resource development in order that the flow data would be directly comparable from year to year. While any development level could have been selected, the 1975 level was used for the Phase I study.

Adjusted Inflow

HEC-PRM utilizes adjusted inflow (or "net" inflows) as input data rather than directly using reservoir inflow, local-flow, and depletions. The adjusted inflow is computed by adding the "reservoir-inflow" and "local-flow" to the corresponding "local-flow depletions". The adjusted inflows are in units of 1000 acre-feet per month. These data are included as Exhibit D-3 of this Appendix. On a network model, all links have a direction definition - flow can go in only one direction. For inflow links, flow starts at the super source and ends at a node. This corresponds to a positive "adjusted inflow". A negative "adjusted inflow" indicates flow would start at a node and end at the super source. However, this violates a network flow programming rule and cannot be done. To facilitate solution, HEC-PRM sets all negative "adjusted inflow" to zero.

Reservoir Evaporation Data

According to the master manual (USACE, 1979, pg. VIII-12), " [e]vaporation from the surface of the main stem reservoirs is a major water loss. Annual evaporation from the reservoirs is estimated to average about three million acre-feet..." This evaporation is accounted for in the network by arc multipliers for each storage arc each period. These multipliers are given by $(1 - ED_{t-1}\,\beta)$ in which ED_{t-1} = evaporation rate, in inches, in period $t\text{-}1$; and β = linear coefficient defining area as function of storage. The linear coefficients for the system reservoirs are shown on Table D-1:

TABLE D-1
Linear Coefficients for Reservoir Storage

Reservoir (1)	Linear Area-Storage Coefficient (Acre/Acre-inches) (2)	Linear Area-Storage Coefficient Acre/Acre-feet) (3)
Ft. Peck	0.0011	0.0132
Garrison	0.0013	0.0156
Oahe	0.0012	0.0144
Big Bend	0.0024	0.0288
Ft. Randall	0.0013	0.0156
Gavins Point	0.0033	0.0396

These coefficients are the slope of a linear approximation to the area-storage relationship. Plots of the area-capacity relationships with the linear approximations are included as Exhibit D-4 of this Appendix. The linear approximation is fitted "by eye".

Annual evaporation depths are provided in machine-readable form for the six reservoirs. The resultant depths are tabulated in Exhibit D-5 of this Appendix. These annual values are distributed to monthly values using the distribution shown on Table D-2.

TABLE D-2
Annual Evaporation Rates

Month (1)	Percent of Annual Evaporation (2)
Jan	0
Feb	0
Mar	0
Apr	0
May	7
Jun	5
Jul	19
Aug	20
Sep	19
Oct	13
Nov	12
Dec	5

Hydraulic Capacities

For the network model, physical limitations on flow and storage must be defined explicitly. For the reservoirs of the Missouri River main stem system, release capacities are given on Table D-3.

TABLE D-3
Maximum Release Capacities of Main Stem Reservoirs

Reservoir (1)	Max. Spillway Discharge, in cfs (2)	Max. Outlet Discharge,(1) in cfs (3)	Max. Power Discharge, in cfs (4)
Ft. Peck	230,000	45,000	16,000
Garrison	660,000	98,000	38,000
Oahe	80,000	111,000	54,000
Big Bend	270,000	0	103,000
Ft. Randall	508,000	128,000	44,500
Gavins Point	345,000	0	36,000

(1) Non power releases
The maximum possible release from each reservoir each period for the network model is the sum of cols. 2, 3, and 4. *Requirements for a System Model* ... (USACE, 1990b) describes how these limitations would be imposed as inviolable constraints on network arcs. For the Phase I model, these limitations can be imposed through the penalty functions.

The reservoir storage capacities are on Table D-4. The reservoir elevation-storage relationships are graphically depicted in Exhibit D-2.

TABLE D-4
Reservoir Storage Information

Reservoir (1)	Top Inactive Storage, in 1000 Acre-ft (2)	Top Carry-over, Multiple-use Storage, in 1000 Acre-ft (3)	Top Flood-Control & Multiple-use Storage, in 1000 Acre-ft (4)	Top Exclusive Flood-control Storage, in 1000 Acre-ft (5)
Ft. Peck	4,211	14,996	17,714	18,688
Garrison	4,990	18,210	22,430	23,924
Oahe	5,451	19,054	22,240	23,337
Big Bend	1,696	-	1,813	1,873
Ft. Randall	1,568	3,267	4,589	5,574
Gavins Point	340	-	432	492

These storage values are gross storage defined in the master manual. MRD has divided the storage in individual reservoirs into operational zones in order to obtain the maximum possible service to all of the multipurpose functions consistent with the physical and authorizing limitations of the projects. The reservoir regulation master manual (USACE, 1979, pages V-1 and V-2) describes these operational zones as follows:

> *5-2. Operational Zones. The operational zones, and governing criteria for operation in these zones considered necessary to achieve the multipurpose benefits for which the reservoirs were authorized, are as follows:*

a. <u>Exclusive Flood Control Reserve.</u> A top zone in each reservoir reserved exclusively for flood control. The storage space therein is utilized only for detention of extreme or unpredictable flood flows, and is evacuated as rapidly as feasible within limitations imposed by considerations of flood control. These considerations include project release limitations, status of storage in the other main stem projects and the level of system releases being maintained, as designated by criteria discussed in Sections IX and X.

b. <u>Annual Flood Control and Multiple-Use Capacity.</u> An upper "normal operating zone" is reserved annually for retention of normal flood flows and for annual multiple-purpose regulation of the impounded flood waters. The capacity in this zone, which is immediately below the top zone of exclusive flood control reserve, will normally be evacuated to a predetermined level by about 1 March to provide adequate storage capacity for the flood season. This level will remain more or less fixed from year to year. During the flood period, water will be impounded in this space as required by consideration of flood control and in the interests of general conservation functions on an annual basis. The evacuation of flood control and multiple-use storage capacity is scheduled to maximize service to the conservation functions. Schedules are limited by the flood control function in that the evacuation must be completed by the beginning of the next flood season, provided such evacuation is possible without contributing to serious downstream flooding.

c. <u>Carry-Over Multiple-Use Capacity.</u> An intermediate zone provides a storage reserve for irrigation, navigation, power production, and other beneficial conservation uses. At the major projects (Ft. Peck, Garrison and Oahe) the storage space in this zone will provide carry-over storage for maintaining downstream flows through a succession of well below normal runoff years. It will be used to provide annual regulation in the event the storage in the annual flood control and multiple-use zone is exhausted. Storage space assigned to this zone in the Ft. Randall project serves a different purpose. A portion of the Ft. Randall space will be evacuated each year immediately preceding the winter season to provide recapture space for upstream winter power releases. The recapture operation results in complete refill of the space during the winter months. Deliberate long-term drawdown into the Ft. Randall carry-over zone is not contemplated. While a minor amount of space in the big Bend and Gavins Point projects was initially provided in this zone, deliberate drawdown into these projects has been reassigned into the lower inactive storage zones.

d. <u>Inactive Capacity.</u> A bottom inactive zone provides minimum power head and sediment storage capacity. It also serves as a minimum pool for recreation, fish and wildlife, and an assured minimum level for pump diversion of water from the reservoir. Reservoir drawdown into this zone will not be scheduled except in an unusual emergency.

Storage limitations ideally will be imposed as inviolable constraints on network arcs that represent storage links. For the Phase I model, these limitations can be imposed through the penalty functions, upper, and lower bounds.

Initial Storage

Initial storage must be specified for each system reservoir. For the critical-period analysis, the starting storage for each reservoir is set to values provided by MRD. The initial storage values are provided on Table D-5.

TABLE D-5
Initial and Ending Storage Values

Reservoir (1)	Initial Storage, in 1000 Acre-ft (2)
Ft. Peck	14,626
Garrison	17,778
Oahe	18,804
Big Bend	1,697
Ft. Randall	3,473
Gavins Point	432

SYSTEM PENALTY FUNCTIONS

Goals of and constraints on Missouri river reservoir system operation are represented with system penalty functions. These functions represent the economic, social, and environmental costs associated with failure to meet operation goals. The costs are related to flow or storage or both at selected system locations. For the Phase I study, functions were developed by the Institute for Water Resources (IWR). These functions are presented in a separate document (USACE, 1990c).

REFERENCES

U.S. Army Corps of Engineers (1979). *Missouri River Main Stem Reservoir System Reservoir Regulation Manual: Master Manual.* U.S. Army Engineer Division, Missouri River, Omaha, NE.

U.S. Army Corps of Engineers (1990a). *Plan of Study for the Review and Update of the Missouri River Main Stem Reservoir System Reservoir Regulation Manual.* U.S. Army Engineer Division, Missouri River, Omaha, NE.

U.S. Army Corps of Engineers (1990b). *Requirements for System Model of Missouri River Main Stem Reservoir System.* Hydrologic Engineering Center, Davis, CA.

U.S. Army Corps of Engineers (1990c). *Penalty Functions for Missouri River Main Stem Reservoir System Study.* Institute for Water Resources, Ft. Belvoir, VA.

EXHIBIT D-1 LOCAL INFLOW

Location: Fort Peck Reservoir Data: Local Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	407	863	867	555	300	218	236	301	298	303	248	317
1931	557	387	432	424	230	224	210	220	179	157	196	157
1932	303	532	825	1406	516	422	240	260	218	194	222	212
1933	488	434	908	1412	430	270	256	226	339	177	315	450
1934	516	722	781	811	290	141	137	204	256	210	198	236
1935	309	428	593	819	409	228	228	262	182	190	179	167
1936	613	430	823	569	264	230	220	246	244	196	169	145
1937	341	383	385	577	343	182	184	260	163	137	186	204
1938	599	327	756	1682	1349	298	317	272	327	272	254	208
1939	891	585	871	863	311	208	210	238	244	222	198	246
1940	399	415	619	619	236	192	212	246	186	262	226	230
1941	359	327	335	613	347	228	305	411	347	349	282	298
1942	629	825	1131	2061	599	329	282	331	357	301	325	633
1943	785	1117	1115	2892	1002	426	317	399	375	335	301	290
1944	678	456	565	1740	914	375	309	339	327	270	375	343
1945	492	353	613	1275	569	262	292	345	288	242	351	413
1946	450	514	710	855	540	258	359	385	303	399	415	422
1947	1226	960	1547	1500	659	272	361	524	407	381	367	351
1948	504	879	1654	3255	1309	541	405	422	417	256	325	294
1949	849	803	1150	1012	440	290	208	323	384	232	244	352
1950	593	773	796	1808	914	548	444	487	402	438	413	374
1951	795	897	1430	1465	829	431	522	578	508	349	344	492
1952	977	1481	1619	1037	559	382	347	325	304	297	315	361
1953	443	376	1100	3096	677	335	293	293	279	308	259	447
1954	412	496	719	861	497	399	245	357	362	317	261	326
1955	373	629	674	821	615	341	330	364	223	337	334	360
1956	575	490	796	978	357	389	364	380	373	337	333	411
1957	678	514	627	1103	514	351	409	425	445	407	402	393
1958	532	505	722	859	649	423	422	462	443	393	347	329
1959	1234	470	873	1269	760	377	347	448	643	833	335	386
1960	833	661	936	732	341	336	369	414	414	335	345	367
1961	303	257	377	470	311	315	322	350	395	323	368	417
1962	557	446	823	1307	547	387	420	447	350	274	309	641
1963	450	356	595	1248	563	378	389	373	335	356	352	349
1964	362	390	1212	2741	1027	547	396	449	424	444	567	636
1965	725	1201	1446	1720	1287	653	738	1067	823	501	467	446
1966	854	627	734	624	522	378	357	322	342	431	483	588
1967	843	588	897	2359	1149	531	545	451	459	388	557	635
1968	891	666	852	1335	763	555	477	598	561	406	529	531
1969	1178	1160	1033	924	1256	567	481	387	463	450	430	501

Location: Garrison Reservoir Data: Local Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	1311	1267	1035	1795	976	883	603	541	415	212	190	290
1931	260	385	653	1634	397	339	186	339	224	180	198	173
1932	501	1216	1500	3011	1583	415	432	450	323	250	284	212
1933	1422	625	1632	2876	797	383	581	375	387	131	296	436
1934	645	561	766	837	246	208	161	282	254	109	113	256
1935	397	609	538	2559	1730	403	232	230	212	278	177	190
1936	819	996	1146	1797	659	365	220	383	363	258	167	167
1937	469	649	764	2271	1381	327	208	409	266	200	258	161
1938	1170	577	1014	3189	2138	484	393	417	266	58	341	159
1939	2053	682	1244	2245	837	309	248	432	365	272	145	206
1940	327	821	1000	1726	635	224	177	617	260	349	248	260
1941	391	746	920	2106	659	724	960	984	601	442	268	361
1942	970	889	1410	2963	1626	492	343	440	464	250	296	776
1943	1724	2864	1289	3648	3076	891	518	575	506	218	290	327
1944	920	2063	1228	4346	2469	567	395	460	428	250	238	365
1945	1527	637	780	2362	2194	700	504	498	333	292	415	315
1946	1089	645	930	2136	1557	391	492	690	440	333	286	526
1947	1678	1718	1771	2803	2344	970	476	549	371	280	290	266
1948	956	1317	1220	3511	1787	583	256	403	311	-28	222	224
1949	1212	1674	1125	2101	1037	272	303	549	523	160	294	324
1950	578	2438	1026	2348	2101	797	587	746	294	372	365	336
1951	627	2022	1336	2199	1757	1123	850	722	521	117	369	489
1952	457	4797	2023	2226	1267	586	403	462	472	241	299	390
1953	511	643	831	2820	1373	587	334	449	507	299	292	608
1954	583	1256	1094	1217	1356	610	454	316	423	329	176	306
1955	517	1628	1303	1691	1053	406	255	424	308	448	515	380
1956	841	948	1176	2523	1091	528	453	419	519	293	294	313
1957	722	742	1206	3150	1926	512	549	579	582	375	375	339
1958	607	684	905	1674	873	365	350	441	374	324	298	236
1959	1817	621	611	1884	1135	304	339	531	305	460	209	339
1960	1997	839	498	1178	296	178	191	256	257	120	198	222
1961	454	216	220	1192	208	131	405	509	404	155	248	482
1962	785	1039	1361	2664	1956	653	470	610	437	302	186	605
1963	1008	547	1180	3314	1256	316	456	468	348	207	307	252
1964	381	647	1089	2781	2104	430	442	400	333	231	384	306
1965	477	2039	1669	2936	3009	866	680	729	342	286	190	212
1966	919	492	672	1094	642	167	252	300	301	217	173	257
1967	1137	1340	1302	3493	2899	507	463	470	470	274	474	423
1968	1286	542	624	2867	1407	834	738	561	598	276	329	323
1969	1477	2077	1351	1700	1884	403	261	377	448	284	214	415

Location: Oahe Reservoir Data: Local Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	676	385	236	151	-99	52	8	125	-69	-81	6	71
1931	83	125	-8	6	58	48	18	2	0	22	-32	60
1932	381	421	242	637	-133	151	32	-12	-40	-139	-8	-32
1933	180	141	647	52	44	42	85	38	34	30	-30	-149
1934	188	2	-44	-46	77	50	20	28	24	-50	-22	44
1935	121	200	151	452	79	20	16	4	-42	-61	-8	-2
1936	393	208	-8	-91	-12	40	18	2	10	-8	-30	-10
1937	202	270	14	712	329	65	28	-10	-44	-16	10	34
1938	347	60	93	315	216	-22	69	18	-77	-83	28	12
1939	934	-345	105	198	83	34	54	8	-6	8	18	8
1940	22	202	77	52	6	24	65	28	-67	30	14	16
1941	113	329	75	1085	117	-48	36	60	0	-65	8	4
1942	109	333	1174	522	163	60	-24	24	-54	22	54	226
1943	986	1323	40	803	58	38	42	-18	79	-111	44	60
1944	18	1644	228	1299	40	145	61	30	153	-105	16	365
1945	1392	284	79	414	79	173	12	83	89	62	24	42
1946	317	60	258	628	224	18	107	131	44	40	2	91
1947	641	540	117	1065	-54	-56	10	71	-95	-54	4	40
1948	927	1121	254	133	89	-2	-34	79	60	-36	46	52
1949	1162	1478	165	115	38	24	6	35	120	18	-42	-33
1950	558	3632	867	212	-115	69	68	48	-90	21	65	4
1951	231	928	-11	207	-6	46	93	58	-186	-141	-33	62
1952	145	3834	222	-6	99	-10	-3	-11	-64	-50	61	41
1953	530	196	342	1165	-28	77	-10	8	-9	-62	0	101
1954	133	277	69	276	-30	70	134	183	121	-44	26	14
1955	221	144	69	50	90	3	26	-4	-40	-20	36	23
1956	684	337	64	76	103	52	28	-1	36	-73	-46	-46
1957	190	86	304	181	119	-51	-21	-15	41	-39	-101	4
1958	249	381	92	141	211	-16	-5	44	-27	-27	32	8
1959	423	204	55	35	2	-29	2	73	-164	78	3	17
1960	484	438	51	76	-69	21	-26	15	-13	-212	65	58
1961	227	-11	98	11	-66	-11	80	-58	64	-206	51	56
1962	319	208	676	770	262	92	32	52	-30	-140	-2	17
1963	278	91	94	260	-14	56	36	33	-58	-206	0	31
1964	81	222	272	553	109	-75	-8	46	-122	-137	31	36
1965	73	436	669	422	106	23	-97	66	25	44	-140	104
1966	1559	357	24	59	114	-9	65	8	48	-30	-32	79
1967	653	229	498	996	50	94	7	58	123	-136	77	32
1968	190	213	17	172	23	-5	60	60	67	14	10	119
1969	521	1006	128	81	458	-16	47	49	66	62	-87	86

Location: Fort Randall Reservoir Data: Local Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	409	-52	-18	-54	-53	61	12	10	-32	-91	-6	169
1931	20	73	67	-95	61	-8	46	4	0	-24	-40	36
1932	188	56	190	180	-163	165	0	-6	-73	-77	0	14
1933	135	129	165	-75	-6	149	-16	26	-22	-48	36	-186
1934	198	0	20	83	93	16	20	-16	-22	-60	-28	18
1935	20	105	186	149	67	-56	22	-18	-42	-91	6	-6
1936	597	32	-63	-65	-40	-6	36	-14	-4	-61	-2	-16
1937	149	18	50	248	-87	28	-63	-34	0	-32	-18	-4
1938	8	127	155	71	-93	-24	52	2	-36	-30	28	-4
1939	490	-347	67	32	-46	34	-28	-42	-16	-14	-46	-24
1940	4	111	20	-115	2	-40	34	-38	-12	-40	-10	-22
1941	0	-4	-65	32	-16	-48	46	73	54	-24	-32	-52
1942	-2	149	1660	426	-50	125	67	10	8	-4	4	-44
1943	93	-20	54	230	-28	-4	4	-32	71	-99	6	-26
1944	117	224	214	490	179	180	54	-8	50	-174	-69	55
1945	421	60	-4	-10	8	63	-60	2	16	-36	8	40
1946	131	139	89	68	79	79	68	87	97	-143	2	12
1947	214	141	-83	395	-179	-2	-60	-8	18	-99	65	111
1948	238	-10	44	75	-141	10	4	-145	52	-38	-38	10
1949	555	-14	186	16	-91	-26	-6	60	6	-14	-72	36
1950	411	234	204	-13	42	34	7	28	0	-30	28	4
1951	145	104	76	233	67	23	58	98	94	3	52	121
1952	379	1347	112	114	54	5	-58	-36	-24	-65	-34	50
1953	615	226	569	178	254	209	95	182	27	-52	48	92
1954	92	-36	-8	160	12	55	4	-29	-1	-47	-43	13
1955	404	87	49	166	18	126	109	138	-144	48	7	14
1956	52	66	91	89	7	91	-10	-53	44	-44	-23	13
1957	77	111	224	210	92	-2	22	8	67	-26	-45	26
1958	149	180	49	21	45	-48	-26	33	-3	-14	14	2
1959	61	4	69	22	10	4	46	3	-17	38	-8	34
1960	750	375	108	94	17	63	-1	59	-12	-6	39	45
1961	45	31	124	113	52	3	3	-9	44	-38	29	25
1962	210	155	483	635	411	76	-54	-51	-5	57	27	164
1963	136	28	115	214	113	11	-41	19	-64	208	173	80
1964	11	191	191	207	71	58	-34	-40	25	177	137	118
1965	87	78	238	136	105	77	95	-22	-31	94	212	97
1966	593	163	97	146	126	171	81	71	30	130	51	86
1967	133	90	159	666	90	66	80	52	41	50	87	128
1968	72	244	94	356	100	85	55	-10	3	-34	216	60
1969	331	339	66	79	149	73	15	36	42	9	158	79

Location: Gavins Point Reservoir Data: Local Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	137	163	196	121	69	81	91	111	99	107	109	137
1931	125	129	105	79	65	71	67	85	77	103	79	135
1932	133	113	143	147	71	69	71	91	89	65	103	83
1933	151	105	131	67	73	91	73	87	97	79	107	97
1934	125	95	85	81	54	67	101	93	95	77	69	133
1935	125	147	119	133	75	65	69	83	95	77	79	79
1936	212	121	129	75	46	58	63	93	85	107	77	83
1937	79	111	60	67	87	83	155	93	54	91	81	93
1938	141	131	105	71	87	85	91	95	83	91	95	63
1939	155	131	71	58	84	95	85	105	89	83	79	93
1940	167	133	87	109	48	61	63	77	81	111	75	93
1941	131	117	85	89	81	67	75	97	91	83	85	91
1942	143	129	339	149	83	77	85	93	91	87	67	117
1943	137	117	99	139	73	65	65	83	93	77	89	87
1944	177	182	145	218	137	103	79	101	107	87	113	133
1945	214	139	115	173	91	111	81	99	97	64	107	123
1946	165	101	111	89	77	74	115	157	115	93	99	109
1947	173	159	115	488	171	34	155	107	40	34	60	97
1948	141	262	149	397	268	186	20	157	67	52	61	91
1949	438	240	222	153	143	56	163	139	79	16	94	55
1950	214	445	125	97	248	178	87	151	137	80	74	91
1951	178	291	229	263	93	274	256	151	106	76	89	164
1952	652	221	239	133	118	115	82	75	66	45	140	118
1953	334	125	166	75	13	-2	-42	-29	148	158	77	163
1954	165	104	130	241	-59	61	53	115	136	141	37	42
1955	274	82	70	58	26	-135	-28	-34	103	88	69	78
1956	178	55	-4	-119	-38	6	-6	164	165	128	71	126
1957	193	173	259	250	160	104	93	116	162	126	85	93
1958	162	230	126	138	177	114	65	93	132	74	61	101
1959	196	98	205	86	70	105	92	114	160	112	69	93
1960	446	361	290	128	83	120	108	114	139	92	74	161
1961	179	84	161	118	103	95	92	148	108	56	55	106
1962	448	206	272	424	466	179	145	147	160	99	91	153
1963	213	157	156	182	141	98	119	100	105	85	89	112
1964	134	200	174	220	138	124	110	102	112	45	78	89
1965	87	142	116	158	54	76	119	133	138	123	58	121
1966	265	156	116	125	81	112	83	76	114	29	124	90
1967	125	87	118	349	107	100	118	135	150	35	115	108
1968	134	164	134	158	126	79	99	146	137	39	106	82
1969	254	304	163	142	136	191	189	221	178	62	102	143

Location: Sioux City   Data: Local Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	93	77	171	119	32	20	20	12	18	0	12	16
1931	20	20	0	50	61	0	4	0	18	0	20	36
1932	280	119	69	119	139	61	56	12	4	0	10	10
1933	50	40	20	10	10	18	100	8	0	0	12	22
1934	14	18	0	65	28	24	14	0	14	8	6	8
1935	65	0	40	0	36	75	16	0	26	0	0	-8
1936	371	85	65	0	67	16	54	0	0	50	0	0
1937	137	216	153	54	131	202	30	8	38	10	2	67
1938	391	109	151	42	313	127	149	173	58	12	18	8
1939	0	292	0	16	161	75	32	0	2	20	0	0
1940	44	137	0	58	91	36	14	0	34	0	30	46
1941	177	117	56	0	153	6	34	89	97	14	6	0
1942	101	79	226	180	95	87	173	36	92	16	36	79
1943	0	0	298	71	145	184	0	0	10	0	2	111
1944	175	204	627	69	920	430	226	145	77	-2	6	85
1945	398	306	212	530	212	95	26	16	16	24	-4	89
1946	417	224	0	8	109	50	54	264	200	12	67	56
1947	20	490	319	214	36	123	44	54	127	-30	30	97
1948	421	589	208	200	240	171	93	135	123	58	8	48
1949	363	450	190	186	220	119	107	27	100	-29	-2	24
1950	463	-89	287	496	95	107	89	85	53	-74	-22	60
1951	308	770	426	609	619	275	325	160	4	34	-64	239
1952	384	1046	628	291	352	103	87	60	43	24	17	44
1953	328	211	364	174	-41	215	38	6	22	-20	21	127
1954	254	103	111	493	128	-1	-8	4	27	34	-11	-2
1955	278	-29	-84	-51	-57	-85	-86	-26	-39	21	31	-14
1956	50	57	36	41	35	25	-16	9	3	1	-34	35
1957	64	44	35	237	171	15	0	23	29	14	18	57
1958	58	93	37	13	28	-28	-28	-29	20	7	5	18
1959	65	78	137	81	4	2	-7	-17	-7	52	5	31
1960	194	1687	317	157	113	153	119	14	21	-6	-2	8
1961	334	95	154	162	86	102	62	44	62	-2	-5	41
1962	265	1683	319	823	523	188	66	47	31	13	40	40
1963	86	14	41	68	18	63	20	31	32	-9	70	41
1964	62	116	93	57	-8	48	68	41	53	9	59	42
1965	117	502	269	317	178	34	85	124	48	92	32	254
1966	280	186	152	139	36	54	62	71	50	83	5	94
1967	146	91	66	333	124	4	-14	-39	4	20	-10	49
1968	85	23	19	12	-32	-22	3	84	23	-96	-3	51
1969	119	1665	427	189	279	-4	-5	-16	-26	79	-35	101

Location: Omaha Data: Local Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	240	40	80	0	60	0	60	0	65	12	16	6
1931	20	40	0	0	60	25	79	0	72	2	14	18
1932	85	46	14	7	18	9	72	1	58	-27	31	29
1933	89	104	-297	-308	149	78	-11	22	-17	-2	2	81
1934	-83	13	-213	63	218	34	17	-10	7	16	8	-6
1935	46	-9	54	-55	109	85	20	4	26	-14	-21	-11
1936	133	114	-28	-114	48	32	91	5	-40	45	-13	2
1937	127	40	56	-26	134	236	31	-19	6	-13	-22	39
1938	39	77	104	-239	-18	29	444	90	18	-9	5	5
1939	54	64	-42	19	149	83	45	10	2	29	-2	6
1940	28	36	-2	119	118	135	53	-47	34	16	41	83
1941	115	83	0	25	92	2	73	58	72	109	41	46
1942	158	75	249	334	342	133	27	11	-33	34	36	227
1943	-97	87	-11	92	442	159	84	26	42	-30	15	78
1944	331	-119	115	512	140	147	73	-1	38	-26	17	148
1945	377	293	407	444	239	332	30	16	13	28	78	169
1946	24	42	59	-127	-77	-5	-40	-66	36	62	21	39
1947	49	200	61	84	785	65	-15	-87	-6	-27	-18	249
1948	409	-188	-7	-138	129	108	28	-7	45	14	7	109
1949	299	574	44	85	49	82	-8	8	-35	18	38	36
1950	146	-113	147	241	161	110	55	26	71	57	113	82
1951	455	755	545	392	444	552	284	28	61	79	90	291
1952	165	109	128	105	281	19	26	39	118	54	-10	90
1953	160	224	61	380	256	105	17	-15	101	33	-89	26
1954	134	86	71	589	147	96	49	160	130	61	15	70
1955	146	213	47	60	200	-49	72	15	103	-25	13	24
1956	73	25	40	6	23	-8	-4	57	72	-24	-10	-4
1957	64	-57	31	289	61	-12	53	59	133	54	26	39
1958	120	34	-16	12	16	-7	-5	-11	87	-13	-27	-16
1959	63	-72	202	298	78	44	26	33	140	56	-25	54
1960	11	724	356	257	62	60	25	33	127	67	41	169
1961	543	130	24	154	-5	40	57	158	82	2	17	121
1962	705	497	300	357	415	149	271	83	87	69	47	104
1963	201	49	75	311	31	66	58	6	91	53	68	72
1964	-4	50	188	40	32	31	84	18	51	12	66	133
1965	476	936	193	139	52	29	124	79	57	31	26	217
1966	23	102	66	54	21	65	32	10	49	12	-14	26
1967	128	57	13	776	62	14	2	14	29	11	19	-24
1968	-29	6	13	70	7	32	45	118	7	74	-60	0
1969	353	914	219	249	392	55	100	52	47	47	38	120

Location: Nebraska City Data: Local Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	430	530	1350	710	420	310	440	510	558	429	354	499
1931	470	500	362	190	180	117	184	184	238	360	232	512
1932	896	455	303	821	309	516	227	281	291	115	366	248
1933	542	493	594	259	370	215	301	214	262	335	269	331
1934	360	298	131	189	102	91	163	170	208	126	116	344
1935	354	280	724	1352	347	219	206	163	266	188	47	91
1936	1009	285	331	177	81	80	146	106	151	142	5	233
1937	696	265	265	313	283	211	147	131	161	169	242	202
1938	490	323	467	250	379	212	361	175	197	242	230	173
1939	498	371	214	233	170	128	70	101	117	138	80	139
1940	425	216	227	472	82	162	72	76	167	103	153	278
1941	312	266	194	273	147	28	177	170	150	241	166	255
1942	401	204	562	800	430	167	412	156	242	199	206	505
1943	311	228	261	816	493	106	154	136	180	91	227	250
1944	559	824	1043	1377	508	307	187	148	184	126	251	337
1945	601	619	594	1171	623	245	116	205	209	81	246	361
1946	391	271	210	465	188	118	184	597	422	363	197	326
1947	473	420	328	1884	862	121	93	157	308	312	146	391
1948	1062	237	258	113	312	549	267	164	194	277	221	324
1949	1785	710	639	903	554	195	261	252	281	215	174	363
1950	745	493	826	378	755	455	139	266	177	158	151	260
1951	944	573	912	1331	781	562	537	496	454	345	406	732
1952	830	644	886	781	419	344	216	245	212	310	371	427
1953	621	466	695	518	293	136	67	154	246	301	181	423
1954	427	399	472	629	95	220	121	230	260	227	191	244
1955	521	197	146	336	138	75	75	198	203	90	177	249
1956	280	224	234	192	147	126	74	150	166	107	101	211
1957	316	319	457	843	416	215	232	277	266	300	191	307
1958	632	626	396	321	847	661	254	175	310	172	213	371
1959	636	500	938	457	305	431	173	282	317	272	180	366
1960	643	1612	1032	917	426	374	278	290	329	228	211	311
1961	523	426	458	536	217	192	190	338	360	251	238	374
1962	1003	772	569	986	531	391	293	328	326	231	171	326
1963	773	392	310	459	156	151	225	214	273	107	227	312
1964	379	435	513	972	321	204	264	205	227	254	233	276
1965	824	704	838	802	627	168	788	726	457	412	254	469
1966	575	425	296	357	168	372	195	196	217	216	15	289
1967	276	240	188	2315	522	187	135	230	268	240	27	424
1968	333	307	250	267	157	156	151	352	353	262	154	290
1969	1087	682	409	426	470	108	121	340	302	335	148	459

Location: Kansas City   Data: Local Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	240	310	1650	1160	330	310	510	310	340	272	166	170
1931	220	330	420	420	501	414	668	466	1890	806	1124	750
1932	589	781	480	1271	976	769	535	194	203	215	253	112
1933	38	482	315	61	349	346	518	224	78	212	96	122
1934	56	116	53	123	224	62	185	193	245	183	90	133
1935	192	25	1645	3353	1284	301	640	322	438	209	95	415
1936	847	391	871	537	247	87	358	224	47	34	29	775
1937	678	243	368	0	773	527	227	41	117	0	44	96
1938	0	469	1268	1006	494	621	332	197	124	89	8	151
1939	732	415	57	1104	760	580	153	42	34	94	0	69
1940	250	67	379	249	286	613	330	108	148	83	296	270
1941	187	362	395	2356	649	423	1112	3201	1377	732	664	552
1942	864	816	1623	2484	1207	849	1436	583	288	585	446	629
1943	133	353	951	4174	860	484	187	168	167	185	74	104
1944	863	3123	2911	1117	1596	1755	1209	549	412	1197	433	542
1945	1620	3131	4038	2821	2315	902	267	373	269	90	448	356
1946	783	541	457	589	726	402	1091	738	636	376	178	51
1947	562	2222	993	4890	1999	266	103	104	296	307	169	178
1948	2081	611	650	555	1715	1056	244	48	268	268	651	1524
1949	1875	594	1062	3255	1810	466	959	546	245	371	203	312
1950	-11	-250	1911	951	2740	1995	966	1397	426	221	264	366
1951	429	755	3153	5906	9363	2207	3460	1110	944	355	381	518
1952	1501	914	1638	725	987	656	548	183	453	327	88	429
1953	133	358	333	-119	304	87	78	67	186	143	79	122
1954	-38	118	363	1069	197	1006	142	321	151	96	62	497
1955	388	306	224	584	386	-58	17	148	219	17	98	75
1956	44	82	107	208	543	251	91	79	154	97	58	70
1957	48	249	704	1553	1087	295	384	471	394	247	229	239
1958	1170	567	974	796	3304	1612	1713	648	628	278	172	562
1959	930	937	2040	1168	1145	485	706	1373	476	365	878	768
1960	1523	3005	1386	1299	1079	701	624	319	334	322	142	366
1961	1481	1279	2054	1725	1046	514	1922	1855	2213	630	664	2374
1962	1568	1101	939	1635	1206	610	791	636	430	333	141	366
1963	994	393	932	354	397	245	274	232	266	122	196	128
1964	58	407	571	1748	724	183	543	206	334	209	327	263
1965	1636	750	386	1907	3590	492	2026	1002	581	519	317	269
1966	397	333	392	755	219	245	261	159	276	144	148	142
1967	-6	398	216	4311	1233	464	583	976	462	365	346	286
1968	187	577	342	326	646	1477	370	782	531	576	460	910
1969	1835	2020	2134	1751	1937	568	553	557	523	527	69	211

Location: Boonville Data: Local Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	240	170	480	310	200	50	70	40	40	140	-20	40
1931	230	590	390	550	139	130	430	630	2260	1160	1490	230
1932	305	521	215	447	525	991	142	92	119	582	295	110
1933	100	446	583	75	291	214	123	246	0	121	0	36
1934	0	197	16	0	123	113	274	285	714	737	410	475
1935	535	214	2693	3802	1212	177	131	112	344	217	59	470
1936	641	211	218	144	129	63	265	436	90	75	373	2044
1937	943	328	921	0	530	304	126	21	60	9	43	33
1938	0	758	853	421	23	267	32	180	97	121	19	58
1939	666	981	102	849	359	389	105	34	19	47	0	22
1940	354	169	363	129	133	528	162	8	81	99	468	386
1941	95	267	115	445	311	37	133	1186	1197	632	376	1089
1942	985	926	867	1351	1364	119	346	312	427	815	346	422
1943	297	142	2610	2283	399	308	133	66	10	151	-19	118
1944	938	3217	1503	-36	26	383	339	255	134	587	32	408
1945	1247	2241	1576	1965	276	72	280	290	128	128	1642	219
1946	1004	611	926	169	396	255	-59	175	304	360	89	90
1947	907	2478	463	5399	2107	96	136	8	228	416	220	236
1948	1656	308	472	626	320	106	50	-75	66	108	391	938
1949	472	555	202	783	585	167	316	326	129	311	613	599
1950	318	-58	652	1050	247	781	97	129	234	51	141	517
1951	513	1490	845	1035	4722	939	1215	351	710	562	499	452
1952	1871	544	1382	481	478	213	120	-59	54	137	-21	146
1953	415	1217	929	234	426	67	20	-37	94	82	12	-65
1954	136	113	227	376	33	91	41	307	154	15	397	591
1955	507	118	446	242	231	222	36	305	113	25	16	-13
1956	-209	-52	-52	-44	309	175	-91	22	38	53	70	49
1957	28	225	375	82	391	113	187	271	221	486	127	261
1958	1005	299	553	673	2116	1440	72	275	511	93	59	599
1959	1011	807	447	707	156	396	259	844	123	231	936	365
1960	86	2933	1882	623	1169	84	261	60	314	62	149	254
1961	1941	1693	1323	323	1019	380	2616	997	3408	528	639	2036
1962	1578	460	190	916	234	241	107	397	86	175	1	143
1963	800	20	477	104	161	52	-7	0	37	53	50	58
1964	-45	830	240	1112	322	-39	462	-46	143	237	1063	571
1965	1465	1609	292	353	1881	370	2065	420	218	310	289	156
1966	203	329	485	849	266	196	0	73	48	227	123	144
1967	121	1627	376	2662	1159	193	125	647	759	440	282	393
1968	98	849	604	250	248	423	108	87	288	268	490	752
1969	633	1403	965	1544	3658	226	717	1376	281	164	335	137

Location: Hermann

Data: Local Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	510	200	550	540	230	80	340	160	180	510	130	260
1931	390	310	810	230	270	230	320	470	330	1350	1220	840
1932	561	439	18	0	1134	245	268	235	245	684	1227	709
1933	785	1153	2740	336	428	298	276	526	236	329	192	360
1934	627	482	218	93	208	299	653	563	548	1379	1340	773
1935	2145	1083	1620	7268	1686	392	353	284	1281	1006	311	439
1936	407	459	198	226	179	137	321	717	1159	477	2052	1719
1937	1250	1140	2057	2800	451	400	259	117	159	250	397	1010
1938	829	2292	3117	2478	386	335	210	283	428	354	229	962
1939	1185	2129	1439	521	484	362	303	139	140	104	111	149
1940	595	654	677	638	212	284	388	141	169	253	1123	788
1941	170	2895	578	526	525	146	1021	4885	3696	1098	700	1433
1942	1078	1813	2015	2677	2052	551	950	632	849	2064	2232	660
1943	753	800	8472	3427	983	557	224	412	365	386	344	509
1944	2513	2732	3616	436	489	995	1036	893	284	687	400	737
1945	3389	5928	3133	3753	1678	507	1330	1426	459	304	1666	1354
1946	1023	1009	1760	413	416	1853	169	175	2912	1022	508	360
1947	1187	4893	1774	1327	2464	490	384	381	474	331	686	256
1948	1660	1044	795	2451	2906	1500	429	303	604	491	2287	2743
1949	2241	1539	1139	2428	1700	592	1149	1989	503	1097	2852	1202
1950	1070	962	2433	2375	1516	1858	1390	470	550	338	184	1160
1951	2204	1778	1310	1440	8947	974	3993	1547	2525	1326	1121	1703
1952	2131	1729	1156	384	398	474	207	118	85	258	276	381
1953	739	1250	1196	115	408	273	212	187	191	156	170	63
1954	33	174	418	336	181	18	168	521	294	454	867	1237
1955	1879	872	433	646	547	118	189	905	202	274	251	212
1956	82	118	486	374	337	128	71	60	84	243	236	388
1957	748	1857	2792	1547	1112	141	34	6	232	510	348	400
1958	2830	1374	995	800	3116	2430	819	336	407	396	499	1148
1959	1040	593	652	470	330	214	-27	1706	517	490	728	762
1960	1084	1909	2413	278	247	137	211	156	353	538	253	100
1961	1189	2483	6630	515	870	483	1707	714	2108	855	785	1378
1962	2407	1062	235	633	229	170	305	644	212	175	158	134
1963	798	319	1160	336	179	146	15	-13	116	198	124	94
1964	205	1530	762	1690	522	154	78	117	194	228	470	383
1965	1069	2556	335	1696	1097	435	2712	1008	213	358	797	1310
1966	928	1712	1295	432	491	228	215	95	80	269	214	386
1967	128	773	1253	1760	2333	488	174	516	1650	1907	496	1504
1968	1089	1179	1661	1218	456	945	403	533	1446	1860	2243	2276
1969	1554	2408	1494	2108	3171	614	1054	3478	967	556	371	351

EXHIBIT D-2 DEPLETIONS

Location: Fort Peck Reservoir Data: Depletions (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	1	-4	-80	-214	-307	-139	25	38	35	17	10	5
1931	1	-9	-134	-212	-227	-171	-9	26	36	17	11	6
1932	2	-4	-105	-126	-313	-102	-75	39	38	19	11	6
1933	2	-4	-41	-231	-382	0	-52	32	33	17	10	4
1934	1	-8	-111	-101	-349	-163	11	30	34	16	11	5
1935	1	-7	-10	-194	-267	-127	-46	32	34	17	10	5
1936	1	-6	-83	-190	-297	-76	-25	19	26	12	6	3
1937	0	-6	-105	-124	-301	-154	17	36	34	16	10	6
1938	2	-9	12	-111	-256	-157	-41	39	34	16	10	5
1939	1	-4	-21	-99	-354	-147	-16	41	38	19	12	6
1940	2	-1	-74	-177	-226	-162	-7	45	39	19	11	7
1941	3	0	-25	-118	-279	-79	34	25	25	11	7	3
1942	0	-3	10	-100	-269	-119	-12	34	33	16	10	5
1943	1	-1	-22	-72	-288	-133	-47	38	35	17	10	5
1944	1	-7	-45	-59	-283	-61	-28	11	26	12	7	3
1945	0	-4	-30	-69	-249	-99	6	17	21	8	4	1
1946	-1	-8	-8	-113	-151	-68	15	6	12	2	1	-1
1947	-2	-5	-40	-36	-164	-25	-21	-3	9	1	0	-1
1948	-3	-6	-24	-52	-78	-37	-53	-8	8	-1	-1	-2
1949	-4	-20	-16	-4	-36	-8	-38	-20	-4	-7	-5	-4
1950	-5	-8	-1	-5	-28	10	28	-26	-7	-8	-6	-5
1951	-6	-8	4	45	-9	11	-26	-34	-13	-11	-7	-6
1952	-7	-17	2	39	32	34	-29	-37	-17	-14	-9	-7
1953	-7	-10	20	65	68	40	-21	-44	-21	-17	-11	-8
1954	-8	-10	46	62	86	34	-14	-40	-19	-16	-9	-6
1955	-6	-1	27	79	81	107	-15	-44	-19	-14	-9	-6
1956	-5	-2	37	141	81	61	1	-47	-20	-16	-9	-6
1957	-6	-1	14	89	76	73	5	-40	-16	-13	-8	-5
1958	-4	0	55	32	57	115	7	-26	-15	-12	-8	-5
1959	-4	1	1	106	84	49	-24	-32	-13	-11	-7	-4
1960	-4	1	9	160	99	20	-12	-22	-16	-13	-8	-5
1961	-5	0	5	178	96	51	-38	-30	-18	-14	-9	-6
1962	-5	-2	7	114	80	34	1	-24	-16	-11	-7	-5
1963	-4	-3	14	44	117	74	-10	-27	-18	-12	-8	-5
1964	-4	0	14	54	116	45	5	-26	-23	-15	-9	-6
1965	-5	-2	4	102	91	42	-24	-16	-14	-10	-6	-4
1966	-4	0	35	76	86	66	-15	-20	-16	-11	-7	-4
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0

Location: Garrison Reservoir Data: Depletions (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	5	-26	-104	-297	-388	-58	-102	9	21	13	6	5
1931	1	-8	-159	-320	-394	-219	-71	27	32	19	10	8
1932	3	-4	-200	-179	-426	-294	-105	42	37	21	10	8
1933	3	-4	-168	-348	-412	-96	-116	-19	25	16	6	5
1934	1	-9	-261	-246	-365	-277	-34	-19	19	10	4	3
1935	0	-8	-113	-225	-395	-265	-80	33	36	21	10	8
1936	3	-2	-162	-235	-294	-175	-73	61	41	21	10	8
1937	5	-2	-75	-152	-201	-260	-78	57	39	19	9	8
1938	3	-4	-32	-216	-310	-171	-72	45	39	20	9	8
1939	4	-3	-62	-170	-308	-157	-53	28	28	14	5	5
1940	2	-2	-97	-226	-280	-185	1	50	35	18	8	7
1941	4	0	-92	-136	-261	-132	-12	46	29	14	6	6
1942	3	-4	-26	-201	-292	-200	-30	68	43	22	11	9
1943	5	0	-39	-165	-307	-199	-77	57	43	23	10	9
1944	5	0	-56	-117	-269	-207	-51	49	43	23	12	9
1945	5	-3	-46	-85	-285	-180	-4	26	30	15	8	6
1946	3	-15	-17	-155	-233	-153	-13	39	24	12	4	5
1947	2	-4	-34	-72	-240	-154	-35	30	19	8	2	3
1948	0	-4	-46	-88	-208	-134	-17	26	24	11	4	4
1949	1	-4	-27	-89	-204	-150	-30	18	13	5	0	1
1950	-1	-5	-13	-91	-140	-109	27	-11	1	-2	-3	-1
1951	-3	-7	-24	-44	-101	-96	-24	6	6	1	-2	0
1952	-3	-5	7	-39	-82	-63	-30	-11	1	2	-4	-2
1953	-3	-7	-13	-13	-49	-73	-30	-4	-2	0	-5	-2
1954	-4	-11	19	31	16	-68	-43	-21	-10	-6	-9	-4
1955	-4	-4	9	38	-7	1	-3	-3	-9	-4	-7	-3
1956	-3	-2	17	114	18	-52	-19	-36	-21	-12	-12	-6
1957	-6	-7	1	45	29	-41	-14	-16	-7	-4	-6	-2
1958	-3	-4	67	15	-6	1	-8	-29	-13	-7	-9	-5
1959	-4	-6	26	82	45	-16	-29	-51	-31	-19	-13	-9
1960	-8	-11	57	95	100	-26	18	-36	-23	-14	-9	-6
1961	-6	-5	25	166	79	7	-53	-26	-15	-9	-7	-4
1962	-5	-4	4	89	63	-3	-27	-31	-17	-10	-7	-5
1963	-5	-7	52	83	90	39	-31	-33	-21	-13	-9	-6
1964	-5	-7	33	28	122	-44	-2	-31	-18	-12	-8	-5
1965	-5	-6	28	62	75	-6	-45	-18	-7	-4	-3	-2
1966	-3	-4	51	63	70	-8	-12	-16	-11	-7	-5	-3
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0

Location: Oahe Reservoir | Data: Depletions (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	-2	-11	-27	-82	-83	-22	-30	-2	2	2	1	-1
1931	-2	-11	-33	-69	-55	-38	-20	-5	2	2	1	-1
1932	-1	-9	-19	-63	-71	-51	-29	-3	2	2	1	-1
1933	-2	-9	-18	-79	-50	-38	-25	-9	0	1	1	-1
1934	-2	-12	-63	-46	-41	-44	-20	-6	0	1	1	-1
1935	-2	-9	-16	-59	-76	-51	-25	0	5	4	2	0
1936	0	-6	-56	-81	-69	-27	-18	3	7	5	3	0
1937	0	-5	-23	-61	-40	-74	-23	1	6	4	3	0
1938	0	-5	-16	-55	-55	-53	2	3	5	4	3	0
1939	0	-7	-46	-42	-64	-37	-24	4	5	4	2	0
1940	0	-5	-49	-56	-39	-37	-21	-3	3	3	1	0
1941	-1	-6	-37	-41	-61	-32	5	3	3	2	2	0
1942	0	-5	-10	-38	-58	-49	-7	-4	1	2	1	-1
1943	-1	-6	-13	-42	-61	-42	-22	5	6	4	2	0
1944	0	-5	-29	-48	-52	-22	-20	-3	4	3	2	0
1945	0	-5	-13	-30	-68	-30	-13	-7	0	1	0	-1
1946	-1	-6	-11	-32	-47	-25	-13	-5	-2	0	0	-2
1947	-1	-6	-13	-18	-50	-38	-14	-6	-1	0	0	-1
1948	-1	-6	-9	-14	-27	-23	-15	-10	-4	-2	-1	-2
1949	-2	-7	-14	-19	-21	-22	-12	-10	-4	-2	-1	-2
1950	-2	-6	-9	-10	-18	-13	-8	-6	-2	-1	0	-1
1951	-1	-4	-8	-8	-18	-10	-7	-7	-4	-2	-1	-2
1952	-1	-6	-13	-9	-19	-10	-8	-3	0	0	0	0
1953	0	-2	-2	-4	-9	-9	-5	-2	0	-1	0	0
1954	0	-2	-4	-7	-10	-6	-2	-2	-1	-1	0	-1
1955	0	-1	-2	-2	-10	-10	-1	-3	0	-1	0	-1
1956	-1	-2	-2	-6	2	-6	-4	-3	-1	-1	0	-1
1957	0	-1	-2	0	-1	-6	-2	-2	-1	-1	0	-1
1958	0	-1	-4	5	2	-6	-4	-3	-1	-1	0	-1
1959	-1	-1	-2	10	3	-4	-3	-4	-2	-2	-1	-1
1960	-1	-1	4	9	1	-2	-4	-3	-1	-1	0	0
1961	0	-1	-5	11	2	-3	-2	-3	-2	-1	0	-1
1962	0	-1	1	7	3	-1	-4	-3	-1	-1	0	0
1963	0	-1	-2	11	11	-2	-1	-4	-2	-2	-1	-1
1964	-1	-1	-3	11	13	-2	-3	-4	-2	-2	-1	-1
1965	-1	-1	4	9	7	-1	-4	-3	-1	-1	-1	0
1966	0	-1	9	15	9	-1	-4	-3	-2	-2	-1	0
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0

Location: Fort Randall Reservoir   Data: Depletions (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	-1	-2	-5	-7	-28	-8	-2	0	0	0	-1	-1
1931	-1	-3	-6	-12	-25	-9	-1	1	0	0	-1	-1
1932	-1	-2	-4	-4	-26	-10	-2	0	0	0	-1	-1
1933	-1	-2	-5	-19	-22	-6	-2	0	0	0	-1	-1
1934	-1	-2	-16	-18	-22	-7	0	0	0	0	-1	-1
1935	-1	-2	-4	-15	-27	-10	-3	2	1	1	-1	0
1936	-1	-1	-7	-22	-26	-3	3	2	1	1	-1	0
1937	-1	-1	-5	-13	-21	-6	1	2	1	0	-1	0
1938	-1	-1	-3	-16	-18	-8	2	2	2	1	0	0
1939	-1	-1	-4	-11	-23	-7	3	2	1	1	0	0
1940	-1	-1	-12	-14	-20	-2	2	2	1	0	0	0
1941	-1	-1	-5	-9	-20	-5	3	2	1	0	0	0
1942	-1	-1	-2	-10	-19	-6	2	2	2	0	0	0
1943	-1	-1	-3	-7	-24	-8	1	1	1	0	0	0
1944	-1	-1	-4	-7	-14	-5	0	1	1	0	0	0
1945	-1	-1	-2	-5	-18	-5	1	1	1	0	0	0
1946	0	-1	-1	-9	-21	-4	3	1	1	0	-1	0
1947	0	-1	-5	-4	-21	-9	2	2	2	0	0	0
1948	0	-1	-2	-5	-17	-6	0	2	2	0	0	0
1949	0	-1	-3	-18	-17	-4	2	3	2	0	0	0
1950	0	-1	-3	-21	-9	-3	3	2	1	0	0	0
1951	0	-1	-1	-4	-13	-3	1	6	3	1	1	0
1952	0	-1	-1	-12	-19	-2	1	2	2	1	0	0
1953	0	0	-2	-6	-16	-4	-1	2	2	1	0	0
1954	0	0	-3	-4	-19	-4	1	2	1	1	0	0
1955	0	0	-2	-7	-19	-4	2	2	2	1	0	0
1956	0	0	-2	-22	-9	-1	1	1	1	0	0	0
1957	0	0	-1	-5	-16	-3	0	2	1	0	0	0
1958	0	0	-5	-7	-8	-8	0	2	2	1	0	0
1959	0	0	-1	-14	-13	-5	3	2	2	1	0	0
1960	0	0	-1	-7	-16	-4	2	2	2	1	0	0
1961	0	0	-1	-13	-11	-4	2	2	1	0	0	0
1962	0	0	-1	-4	-10	-5	1	2	1	0	0	0
1963	0	0	-1	-6	-10	-7	2	2	2	1	0	0
1964	0	0	-1	-8	-14	-4	2	1	0	0	0	0
1965	0	0	-1	-4	-8	-4	2	1	0	0	0	0
1966	0	0	-3	-7	-7	0	2	0	0	0	0	0
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0

Location: Gavins Point Reservoir Data: Depletions (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	0	0	0	-1	-1	-1	-1	0	0	0	0	0
1931	0	0	0	-1	-1	-1	-1	0	0	0	0	0
1932	0	0	0	-1	-1	-1	-1	0	0	0	0	0
1933	0	0	0	-1	-1	-1	-1	0	0	0	0	0
1934	0	0	0	0	-1	-1	-1	0	0	0	0	0
1935	0	0	0	0	-2	-1	-1	0	0	0	0	0
1936	0	0	0	-1	-1	-1	-1	0	0	0	0	0
1937	0	0	0	-1	-1	-1	-1	0	0	0	0	0
1938	0	0	0	0	-1	-1	-1	0	0	0	0	0
1939	0	0	0	0	-1	-1	-1	0	0	0	0	0
1940	0	0	0	0	-1	-1	-1	0	0	0	0	0
1941	0	0	0	0	-1	-1	-1	0	0	0	0	0
1942	0	0	0	0	-1	-1	-1	0	0	0	0	0
1943	0	0	0	0	-1	-1	-1	0	0	0	0	0
1944	0	0	0	0	-1	-1	-1	0	0	0	0	0
1945	0	0	0	0	-1	-1	-1	0	0	0	0	0
1946	0	0	0	-1	-1	-1	-1	0	0	0	0	0
1947	0	0	0	0	-1	-1	-1	0	0	0	0	0
1948	0	0	0	0	-1	-1	-1	0	0	0	0	0
1949	0	0	0	0	-1	-1	-1	0	0	0	0	0
1950	0	0	0	0	-1	-1	-1	0	0	0	0	0
1951	0	0	0	0	-1	-1	-1	0	0	0	0	0
1952	0	0	0	0	-1	-1	-1	0	0	0	0	0
1953	0	0	0	0	-1	-1	-1	0	0	0	0	0
1954	0	0	0	0	-1	-1	-1	0	0	0	0	0
1955	0	0	0	0	-1	-1	-1	0	0	0	0	0
1956	0	0	0	0	-1	-1	-1	0	0	0	0	0
1957	0	0	0	0	-1	-1	-1	0	0	0	0	0
1958	0	0	0	0	-1	-1	-1	0	0	0	0	0
1959	0	0	0	0	-1	-1	-1	0	0	0	0	0
1960	0	0	0	0	-1	-1	-1	0	0	0	0	0
1961	0	0	0	0	-1	0	-1	0	0	0	0	0
1962	0	0	0	0	-1	-1	-1	0	0	0	0	0
1963	0	0	0	0	-1	0	0	0	0	0	0	0
1964	0	0	0	0	-1	0	0	0	0	0	0	0
1965	0	0	0	0	0	0	0	0	0	0	0	0
1966	0	0	0	0	0	0	0	0	0	0	0	0
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0

Location: Sioux City Data: Depletions (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	-19	-10	-23	-24	0	0	0	0	0	0	0	0
1931	0	0	0	0	0	0	0	0	0	0	0	0
1932	-18	-19	-2	-24	-23	0	0	0	0	0	0	0
1933	0	0	0	0	0	0	-16	0	0	0	0	0
1934	0	0	0	0	0	0	0	0	0	0	0	0
1935	0	0	0	0	0	-8	0	0	0	0	0	0
1936	-13	-15	0	0	0	0	0	0	0	0	0	0
1937	-13	-18	-19	0	-15	-36	0	0	0	0	0	0
1938	-15	-16	-18	0	-15	-13	-16	-5	0	0	0	0
1939	0	-18	0	0	-16	-8	0	0	0	0	0	0
1940	0	-16	0	0	-15	0	0	0	0	0	0	0
1941	-13	-23	0	0	-13	0	0	-5	-3	0	0	0
1942	-13	-12	-23	-32	-19	-17	-35	0	-10	0	0	-5
1943	0	0	-19	-4	-29	-37	0	0	0	0	0	-5
1944	-13	-16	-19	-2	-42	-42	-42	-10	-8	0	0	-5
1945	-21	-18	-18	-28	-41	-19	0	0	0	0	0	-5
1946	-16	-21	0	0	-22	0	0	-10	-8	0	0	0
1947	0	-32	-19	-29	0	-24	0	0	-6	0	0	-5
1948	-13	-31	-18	-29	-44	-34	-19	-10	-6	0	0	0
1949	-13	-32	-18	-29	-18	-18	-19	0	-6	0	0	0
1950	-13	0	-51	105	0	-21	-18	-13	0	0	0	0
1951	-11	-31	-16	-28	-39	-34	-28	-8	0	0	0	-3
1952	-11	-29	-16	-24	-39	-19	-16	0	0	0	0	0
1953	-11	-13	-18	-34	0	-41	0	0	0	0	0	-3
1954	-10	-13	-15	-24	-28	0	0	0	0	0	0	0
1955	-10	0	0	0	0	0	0	0	0	0	0	0
1956	-6	0	0	0	0	0	0	0	0	0	0	0
1957	0	0	0	-19	-29	0	0	0	0	0	0	0
1958	-2	-10	0	0	0	0	0	0	0	0	0	0
1959	0	-5	-6	-6	0	0	0	0	0	-1	0	0
1960	-5	-8	-10	-15	-18	-15	-15	0	0	0	0	0
1961	-5	-6	-8	-15	-11	-8	0	0	0	0	0	0
1962	-5	-6	-8	-13	-19	-21	-4	0	0	0	0	0
1963	-3	0	0	0	0	0	0	0	0	0	-2	0
1964	-3	-5	-6	0	0	0	0	0	0	0	0	0
1965	-3	-3	-5	-6	-5	0	-5	-2	0	-2	0	0
1966	-3	-3	-3	0	0	0	0	0	-2	0	0	0
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0

Location: Omaha

Data: Depletions (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	-24	-4	-8	0	-6	0	0	0	0	0	0	0
1931	0	-4	0	0	-6	-3	0	0	0	0	0	0
1932	-9	-5	0	0	0	0	0	0	0	0	0	0
1933	-9	-10	0	0	-15	-8	0	0	0	0	0	0
1934	0	0	0	-6	-22	-3	0	0	0	0	0	0
1935	-5	0	-5	0	-11	-9	0	0	0	0	0	0
1936	-13	-11	0	0	-5	-3	0	0	0	0	0	0
1937	-13	-4	-6	0	-13	-11	0	0	0	0	0	0
1938	-4	-8	-10	0	0	-3	0	0	0	0	0	0
1939	-5	-6	0	0	-15	-8	0	0	0	0	0	0
1940	-3	-4	0	-12	-12	-8	0	0	0	0	0	0
1941	-12	-8	0	-3	-9	0	0	0	0	0	0	0
1942	-16	-8	-25	-33	-25	-10	0	0	0	0	0	0
1943	0	-9	0	-9	-25	-10	0	0	0	0	0	0
1944	-6	0	-6	-8	-6	-2	0	0	0	0	0	0
1945	-25	-25	-25	-37	-24	-10	0	0	0	0	0	0
1946	-2	-4	-6	0	0	0	0	0	0	0	0	0
1947	-5	-20	-6	-8	-23	-7	0	0	0	0	0	0
1948	-23	0	0	0	-13	-10	0	0	0	0	0	0
1949	-23	-23	-4	-9	-5	-8	0	0	0	0	0	0
1950	-15	0	-15	-24	-16	-10	0	0	0	0	0	0
1951	-6	-6	-6	-8	-6	-2	0	0	0	0	0	0
1952	-4	-4	-4	-8	-4	0	0	0	0	0	0	0
1953	-16	-18	-6	-25	-18	-8	0	0	0	0	0	0
1954	-13	-9	-7	-25	-15	-8	0	0	0	0	0	0
1955	-15	-16	-5	-6	-16	0	0	0	0	0	0	0
1956	-7	-3	-4	0	-1	0	0	0	0	0	0	0
1957	-6	0	-3	-18	-6	0	0	0	0	0	0	0
1958	-12	-3	0	0	0	0	0	0	0	0	0	0
1959	-6	0	-12	-16	-8	-4	0	0	0	0	0	0
1960	0	-10	-10	-16	-6	-4	0	0	0	0	0	0
1961	-10	-10	-2	-15	0	-4	0	0	0	0	0	0
1962	-4	-4	-4	-4	-4	-2	0	0	0	0	0	0
1963	-8	-5	-8	-12	-3	-4	0	0	0	0	0	0
1964	0	-5	-5	-4	-3	-2	0	0	0	0	0	0
1965	-4	-4	-4	-6	-4	-2	0	0	0	0	0	0
1966	-1	-4	-4	-5	-1	-1	0	0	0	0	0	0
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0

Location: Nebraska City   Data: Depletions (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	-172	-212	-195	-284	-105	2	-3	-204	-223	-151	-67	-107
1931	-147	-159	-140	-76	-72	-47	-74	-74	-95	-144	-93	-205
1932	-207	-137	-92	-139	-97	-113	-70	-112	-116	-46	-146	-99
1933	-217	-197	-211	-104	-120	-86	-120	-86	-105	-134	-108	-132
1934	-144	-119	-52	-76	-41	-30	-65	-68	-61	-50	-46	-138
1935	-142	-112	-290	-395	-97	-88	-68	-51	-78	-74	14	-30
1936	-323	-80	-107	-71	-20	-19	-58	-42	-60	-57	0	-93
1937	-278	-106	-106	-125	-113	-84	-59	-52	-64	-68	-97	-81
1938	-196	-129	-187	-100	-152	-85	-144	-70	-79	-97	-92	-69
1939	-199	-148	-86	-93	-68	-51	-9	-40	-47	-55	-19	-56
1940	-170	-86	-91	-189	-21	-65	-11	-15	-67	-41	6	7
1941	-41	-28	-36	-71	-59	33	-71	-68	7	17	20	18
1942	7	-43	-69	-137	-162	-67	-157	-58	-18	-72	-82	-102
1943	-34	-74	-102	-102	-131	-42	-62	-54	-58	-30	-91	-72
1944	-44	17	36	-69	-2	-110	-75	-59	-74	-50	-100	23
1945	23	8	11	-125	-115	-98	-46	-82	16	31	-75	-11
1946	-67	-72	-73	-88	-75	-47	-74	-148	-37	-70	-54	-2
1947	-44	-23	-78	-94	-153	-48	-32	-63	-123	47	9	40
1948	-57	-54	-103	-45	-125	-160	-73	-66	-78	-70	18	-17
1949	-108	-73	-31	-110	-159	-78	-104	-101	-99	26	-20	2
1950	-27	-117	-37	-71	-89	-107	-56	-70	-10	-8	-1	9
1951	-8	7	-21	-87	-129	-129	-119	-84	-62	3	-60	-182
1952	-238	-131	-118	-112	-93	-88	-71	-80	-68	-33	-36	-37
1953	-70	-39	-20	-65	-74	-54	-6	-62	-98	-79	-17	-14
1954	-49	-17	-17	-33	-34	-88	-48	-92	-44	-29	-17	-19
1955	-43	-68	-26	-87	-55	-13	-14	-79	-67	-19	-18	-31
1956	-75	-63	-38	-39	-53	-50	-13	-55	-46	-11	0	-4
1957	-31	-21	-142	-113	-72	-69	-67	-59	-52	-52	-44	-42
1958	-98	-109	-121	-123	-98	-73	-54	-46	-38	-16	-21	-17
1959	-70	-90	-29	1	-43	-36	-52	-33	-34	-32	-23	-7
1960	-69	-29	11	1	-32	-27	-50	-62	-17	-10	-3	-1
1961	0	-3	-26	-81	-47	-69	-56	-74	-81	-62	-51	-77
1962	-87	-11	10	-99	-88	-75	-61	-39	-24	-7	13	-24
1963	-40	-27	-27	-42	-13	0	0	-4	-5	-5	-5	-13
1964	0	0	0	0	0	0	0	0	0	0	0	0
1965	-29	-20	-20	-30	-9	0	0	-3	-4	-4	-4	-9
1966	-23	-16	-16	-24	-7	0	0	-2	-3	-3	-3	-7
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0

Location: Kansas City Data: Depletions (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	0	-50	-171	-402	-132	-124	-126	0	0	0	0	0
1931	0	-50	-168	-168	-200	-166	-253	0	0	0	0	0
1932	0	-50	-171	-402	-251	-131	0	0	0	0	0	0
1933	16	-66	-126	-7	-140	-138	-207	-90	-24	-85	-38	-49
1934	-2	-46	1	-49	-90	-8	-74	-77	-98	-73	-36	-53
1935	-77	29	-623	-402	-251	-120	-10	0	0	0	0	0
1936	0	-50	-171	-215	-99	-33	-143	-90	7	20	25	-257
1937	0	-50	-147	54	-309	-211	-91	13	-47	54	10	-38
1938	54	-188	-330	-402	-198	-184	0	0	0	0	46	-46
1939	0	-50	-3	-442	-304	-206	0	12	20	-32	54	-15
1940	-39	-13	-152	-100	-114	-245	-132	-43	-59	-29	-118	0
1941	0	-50	-158	-415	-251	-131	0	0	0	0	0	0
1942	0	-50	-171	-402	-251	-131	0	0	0	0	0	0
1943	0	-50	-171	-402	-251	-131	0	0	0	0	0	0
1944	0	-50	-171	-402	-251	-131	0	0	0	0	0	0
1945	0	-50	-171	-402	-251	-131	0	0	0	0	0	0
1946	0	-50	-171	-236	-290	-161	-97	0	0	0	0	3
1947	-3	-50	-171	-402	-251	-106	-24	0	0	0	0	0
1948	0	-48	-163	-222	-403	-125	0	6	-6	0	0	0
1949	0	-46	-156	-367	-229	-119	0	0	0	0	0	0
1950	65	304	-583	-380	-260	-126	-3	-40	-18	-4	6	12
1951	-3	-50	-34	-1019	-808	802	-5	684	154	-6	-9	-30
1952	-31	-36	-116	-186	-163	-63	-10	7	4	-8	-12	-36
1953	-24	-35	-60	173	-122	-33	15	31	103	-57	-25	-49
1954	92	16	-145	-428	-79	-278	-2	-6	116	-23	-8	-73
1955	-27	-35	-54	-182	-91	112	37	-59	63	37	-39	-21
1956	10	15	-43	-83	-217	-43	46	14	8	2	6	-3
1957	6	-39	-282	-323	-424	-100	-43	-32	3	-29	-21	-5
1958	-11	-49	-28	-125	-4	-86	-12	-33	-29	-14	-11	-3
1959	-3	-46	-28	-140	-85	-13	-32	-15	-9	0	9	6
1960	106	-190	-164	-72	-100	-59	-34	-14	-18	-32	-3	6
1961	13	-33	18	-154	-160	-69	-38	-25	-10	1	13	9
1962	-7	-57	-48	-55	-84	-142	-81	-22	25	24	14	18
1963	-36	-44	-37	-65	-51	-18	-46	0	0	0	0	0
1964	0	-13	-45	-105	-66	-34	0	0	0	0	0	0
1965	0	-11	-37	-87	-55	-28	0	0	0	0	0	0
1966	0	-9	-30	-70	-44	-23	0	0	0	0	0	0
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0

Location: Boonville Data: Depletions (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	-24	-17	-38	-31	-8	0	0	0	0	0	50	-4
1931	-23	-59	-39	-55	-2	0	0	0	0	0	0	-13
1932	-26	-26	-22	-44	0	0	0	0	0	0	0	-11
1933	-10	-45	-27	-8	-29	-3	0	0	30	-12	30	-4
1934	30	-20	14	0	-12	-11	-27	-29	-71	-7	0	-13
1935	-26	-21	-31	-39	0	0	0	0	0	0	0	-13
1936	-26	-21	-22	-14	-13	-6	-16	0	0	0	0	-13
1937	-26	-26	-26	30	-53	-16	0	9	-6	21	-4	-3
1938	30	-76	-63	-39	7	-7	0	0	0	0	11	-6
1939	-45	-26	-10	-56	0	0	0	0	11	-5	30	8
1940	-35	-17	-36	-13	-13	-53	-8	22	-8	-10	-4	-13
1941	-10	-27	-12	-45	-26	0	0	0	0	0	0	-13
1942	-26	-26	-26	-39	0	0	0	0	0	0	0	-13
1943	-26	-14	-38	-39	0	0	0	0	20	-15	49	-12
1944	-81	-25	-25	66	4	-38	-34	-26	-10	0	0	-13
1945	-24	-24	-24	-36	0	0	0	0	0	0	0	-12
1946	-23	-23	-23	-17	-18	0	89	-18	-30	-36	-5	-9
1947	-25	-22	-22	-34	0	0	0	22	-22	0	0	-11
1948	-21	-21	-21	-32	0	0	0	105	-7	-11	-39	-59
1949	-20	-20	-20	-31	0	0	0	0	0	0	0	-10
1950	-20	88	-65	-91	0	0	0	0	0	0	0	-10
1951	-19	-19	-19	-28	0	0	0	0	0	0	0	-9
1952	-18	-18	-18	-26	0	0	0	89	-5	-14	51	-15
1953	-42	-107	-17	-23	-1	0	10	67	-9	-8	18	81
1954	-14	-11	-23	-38	-3	-9	-4	-31	-15	15	-40	-57
1955	-15	-12	-18	-22	0	0	0	0	0	5	14	43
1956	89	0	0	0	-31	-18	48	0	-4	-5	-7	-5
1957	2	-23	-38	-8	-39	-11	-19	-27	-22	-16	0	-6
1958	-12	-12	-12	-17	0	0	0	0	0	0	0	-6
1959	-11	-11	-11	-16	0	0	0	0	0	0	0	-5
1960	-9	-11	-10	-15	0	0	0	0	0	0	0	-5
1961	-9	-9	-9	-13	0	0	0	0	0	0	0	-4
1962	-8	-8	-8	-12	0	0	0	0	0	0	29	-14
1963	-25	10	-23	-10	0	0	37	30	-4	-5	-5	-6
1964	75	-83	-24	-45	0	69	-46	76	-14	-24	-61	-3
1965	-5	-5	-5	-7	0	0	0	0	0	0	0	-2
1966	-4	-4	-4	-6	0	0	31	-7	-5	-19	0	-2
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0

Location: Hermann   Data: Depletions (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	-111	-50	-138	67	104	126	213	-40	-45	-128	-33	-65
1931	-98	-78	-203	67	104	126	213	-118	-74	-28	-27	-46
1932	-111	-110	2	67	104	126	213	-59	-61	-171	-84	-46
1933	-111	-123	-125	67	104	126	213	-116	-59	-33	-27	-46
1934	-111	-121	-55	67	104	126	213	-141	-111	-28	-27	-46
1935	-111	-123	-125	67	104	126	213	-71	-108	-28	-27	-46
1936	-102	-115	-50	67	104	126	213	-179	-93	-28	-27	-46
1937	-111	-123	-125	67	104	126	213	-29	-40	-63	-99	-50
1938	-111	-123	-125	67	104	126	213	-71	-107	-30	-27	-46
1939	-111	-123	-125	67	104	126	213	-35	-35	-26	-28	-37
1940	-149	-164	-167	67	104	126	213	-35	-42	-63	-94	-46
1941	-43	-191	-125	67	104	126	213	-116	-63	-28	-27	-46
1942	-111	-123	-125	67	104	126	213	-116	-63	-28	-27	-46
1943	-111	-123	-125	67	104	126	213	-103	-76	-28	-27	-46
1944	-107	-118	-120	64	100	122	205	-112	-61	-27	-26	-45
1945	-102	-113	-115	62	96	117	196	-107	-58	-26	-25	-43
1946	-99	-109	-112	60	93	113	190	-44	-116	-25	-24	-41
1947	-95	-105	-107	57	89	108	182	-95	-58	-24	-23	-40
1948	-90	-100	-102	55	85	103	173	-76	-70	-23	-22	-38
1949	-86	-95	-97	52	81	98	165	-90	-49	-22	-21	-36
1950	-83	-91	-93	50	78	94	158	-86	-47	-21	-20	-35
1951	-78	-86	-88	47	74	89	150	-82	-45	-20	-19	-33
1952	-74	-82	-83	45	70	84	142	-30	-21	-65	-41	-31
1953	-70	-77	-79	42	66	79	134	-47	-48	-36	-17	-16
1954	-8	-44	-105	40	62	74	125	-130	-44	-17	-16	-27
1955	-62	-68	-70	37	58	71	119	-65	-35	-16	-15	-26
1956	-21	-30	-122	35	54	66	111	-15	-21	-61	-40	-24
1957	-53	-59	-60	32	50	61	102	14	-58	-56	-13	-22
1958	-49	-54	-55	30	46	56	94	-51	-28	-13	-12	-21
1959	-46	-50	-51	28	43	52	87	-48	-26	-12	-11	-19
1960	-41	-46	-47	25	39	47	79	-39	-28	-11	-10	-17
1961	-37	-41	-42	22	35	42	71	-39	-21	-9	-9	-15
1962	-33	-36	-37	20	31	37	63	-34	-19	-8	-8	-14
1963	-28	-31	-32	17	27	32	54	33	-29	-50	-15	-12
1964	-25	-28	-28	15	23	28	48	-26	-14	-6	-6	-10
1965	-21	-23	-23	12	19	24	40	201	-53	-91	-100	-9
1966	-16	-18	-18	10	15	19	31	-17	-9	-4	-4	-7
1967	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0

EXHIBIT D-3 ADJUSTED INFLOW

Location: Fort Peck Reservoir Data: Adjusted Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	408	859	787	341	-7	79	261	339	333	320	258	322
1931	558	378	298	212	3	53	201	246	215	174	207	163
1932	305	528	720	1280	203	320	165	299	256	213	233	218
1933	490	430	867	1181	48	270	204	258	372	194	325	454
1934	517	714	670	710	-59	-22	148	234	290	226	209	241
1935	310	421	583	625	142	101	182	294	216	207	189	172
1936	614	424	740	379	-33	154	195	265	270	208	175	148
1937	341	377	280	453	42	28	201	296	197	153	196	210
1938	601	318	768	1571	1093	141	276	311	361	288	264	213
1939	892	581	850	764	-43	61	194	279	282	241	210	252
1940	401	414	545	442	10	30	205	291	225	281	237	237
1941	362	327	310	495	68	149	339	436	372	360	289	301
1942	629	822	1141	1961	330	210	270	365	390	317	335	638
1943	786	1116	1093	2820	714	293	270	437	410	352	311	295
1944	679	449	520	1681	631	314	281	350	353	282	382	346
1945	492	349	583	1206	320	163	298	362	309	250	355	414
1946	449	506	702	742	389	190	374	391	315	401	416	421
1947	1224	955	1507	1464	495	247	340	521	416	382	367	350
1948	501	873	1630	3203	1231	504	352	414	425	255	324	292
1949	845	783	1134	1008	404	282	170	303	380	225	239	348
1950	588	765	795	1803	886	558	472	461	395	430	407	369
1951	789	889	1434	1510	820	442	496	544	495	338	337	486
1952	970	1464	1621	1076	591	416	318	288	287	283	306	354
1953	436	366	1120	3161	745	375	272	249	258	291	248	439
1954	404	486	765	923	583	433	231	317	343	301	252	320
1955	367	628	701	900	696	448	315	320	204	323	325	354
1956	570	488	833	1119	438	450	365	333	353	321	324	405
1957	672	513	641	1192	590	424	414	385	429	394	394	388
1958	528	505	777	891	706	538	429	436	428	381	339	324
1959	1230	471	874	1375	844	426	323	416	630	822	328	382
1960	829	662	945	892	440	356	357	392	398	322	337	362
1961	298	257	382	648	407	366	284	320	377	309	359	411
1962	552	444	830	1421	627	421	421	423	334	263	302	636
1963	446	353	609	1292	680	452	379	346	317	344	344	344
1964	358	390	1226	2795	1143	592	401	423	401	429	558	630
1965	720	1199	1450	1822	1378	695	714	1051	809	491	461	442
1966	850	627	769	700	608	444	342	302	326	420	476	584
1967	843	588	897	2359	1149	531	545	451	459	388	557	635
1968	891	666	852	1335	763	555	477	598	561	406	529	531
1969	1178	1160	1033	924	1256	567	481	387	463	450	430	501

Location: Garrison Reservoir   Data: Adjusted Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	1316	1241	931	1498	588	825	501	550	436	225	196	295
1931	261	377	494	1314	3	120	115	366	256	199	208	181
1932	504	1212	1300	2832	1157	121	327	492	360	271	294	220
1933	1425	621	1464	2528	385	287	465	356	412	147	302	441
1934	646	552	505	591	-119	-69	127	263	273	119	117	259
1935	397	601	425	2334	1335	138	152	263	248	299	187	198
1936	822	994	984	1562	365	190	147	444	404	279	177	175
1937	474	647	689	2119	1180	67	130	466	305	219	267	169
1938	1173	573	982	2973	1828	313	321	462	305	78	350	167
1939	2057	679	1182	2075	529	152	195	460	393	286	150	211
1940	329	819	903	1500	355	39	178	667	295	367	256	267
1941	395	746	828	1970	398	592	948	1030	630	456	274	367
1942	973	885	1384	2762	1334	292	313	508	507	272	307	785
1943	1729	2864	1250	3483	2769	692	441	632	549	241	300	336
1944	925	2063	1172	4229	2200	360	344	509	471	273	250	374
1945	1532	634	734	2277	1909	520	500	524	363	307	423	321
1946	1092	630	913	1981	1324	238	479	729	464	345	290	531
1947	1680	1714	1737	2731	2104	816	441	579	390	288	292	269
1948	956	1313	1174	3423	1579	449	239	429	335	-17	226	228
1949	1213	1670	1098	2012	833	122	273	567	536	165	294	325
1950	577	2433	1013	2257	1961	688	614	735	295	370	362	335
1951	624	2015	1312	2155	1656	1027	826	728	527	118	367	489
1952	454	4792	2030	2187	1185	523	373	451	473	243	295	388
1953	508	636	818	2807	1324	514	304	445	505	299	287	606
1954	579	1245	1113	1248	1372	542	411	295	413	323	167	302
1955	513	1624	1312	1729	1046	407	252	421	299	444	508	377
1956	838	946	1193	2637	1109	476	434	383	498	281	282	307
1957	716	735	1207	3195	1955	471	535	563	575	371	369	337
1958	604	680	972	1689	867	366	342	412	361	317	289	231
1959	1813	615	637	1966	1180	288	310	480	274	441	196	330
1960	1989	828	555	1273	396	152	209	220	234	106	189	216
1961	448	211	245	1358	287	138	352	483	389	146	241	478
1962	780	1035	1365	2753	2019	650	443	579	420	292	179	600
1963	1003	540	1232	3397	1346	355	425	435	327	194	298	246
1964	376	640	1122	2809	2226	386	440	369	315	219	376	301
1965	472	2033	1697	2998	3084	860	635	711	335	282	187	210
1966	916	488	723	1157	712	159	240	284	290	210	168	254
1967	1137	1340	1302	3493	2899	507	463	470	470	274	474	423
1968	1286	542	624	2867	1407	834	738	561	598	276	329	323
1969	1477	2077	1351	1700	1884	403	261	377	448	284	214	415

Location: Oahe Reservoir Data: Adjusted Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	674	374	209	69	-182	30	-22	123	-67	-79	7	70
1931	81	114	-41	-63	3	10	-2	-3	2	24	-31	59
1932	380	412	223	574	-204	100	3	-15	-38	-137	-7	-33
1933	178	132	629	-27	-6	4	60	29	34	31	-29	-150
1934	186	-10	-107	-92	36	6	0	22	24	-49	-21	43
1935	119	191	135	393	3	-31	-9	4	-37	-57	-6	-2
1936	393	202	-64	-172	-81	13	0	5	17	-3	-27	-10
1937	202	265	-9	651	289	-9	5	-9	-38	-12	13	34
1938	347	55	77	260	161	-75	71	21	-72	-79	31	12
1939	934	-352	59	156	19	-3	30	12	-1	12	20	8
1940	22	197	28	-4	-33	-13	44	25	-64	33	15	16
1941	112	323	38	1044	56	-80	41	63	3	-63	10	4
1942	109	328	1164	484	105	11	-31	20	-53	24	55	225
1943	985	1317	27	761	-3	-4	20	-13	85	-107	46	60
1944	18	1639	199	1251	-12	123	41	27	157	-102	18	365
1945	1392	279	66	384	11	143	-1	76	89	63	24	41
1946	316	54	247	596	177	-7	94	126	42	40	2	89
1947	640	534	104	1047	-104	-94	-4	65	-96	-54	4	39
1948	926	1115	245	119	62	-25	-49	69	56	-38	45	50
1949	1160	1471	151	96	17	2	-6	25	116	16	-43	-35
1950	556	3626	858	202	-133	56	60	42	-92	20	65	3
1951	230	924	-19	199	-24	36	86	51	-190	-143	-34	60
1952	144	3828	209	-15	80	-20	-11	-14	-64	-50	61	41
1953	530	194	340	1161	-37	68	-15	6	-9	-63	0	101
1954	133	275	65	269	-40	64	132	181	120	-45	26	13
1955	221	143	67	48	80	-7	25	-7	-40	-21	36	22
1956	683	335	62	70	105	46	24	-4	35	-74	-46	-47
1957	190	85	302	181	118	-57	-23	-17	40	-40	-101	3
1958	249	380	88	146	213	-22	-9	41	-28	-28	32	7
1959	422	203	53	45	5	-33	-1	69	-166	76	2	16
1960	483	437	55	85	-68	19	-30	12	-14	-213	65	58
1961	227	-12	93	22	-64	-14	78	-61	62	-207	51	55
1962	319	207	677	777	265	91	28	49	-31	-141	-2	17
1963	278	90	92	271	-3	54	35	29	-60	-208	-1	30
1964	80	221	269	564	122	-77	-11	42	-124	-139	30	35
1965	72	435	673	431	113	22	-101	63	24	43	-141	104
1966	1559	356	33	74	123	-10	61	5	46	-32	-33	79
1967	653	229	498	996	50	94	7	58	123	-136	77	32
1968	190	213	17	172	23	-5	60	60	67	14	10	119
1969	521	1006	128	81	458	-16	47	49	66	62	-87	86

Location: Fort Randall Reservoir Data: Adjusted Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	408	-54	-23	-61	-81	53	10	10	-32	-91	-7	168
1931	19	70	61	-107	36	-17	45	5	0	-24	-41	35
1932	187	54	186	176	-189	155	-2	-6	-73	-77	-1	13
1933	134	127	160	-94	-28	143	-18	26	-22	-48	35	-187
1934	197	-2	4	65	71	9	20	-16	-22	-60	-29	17
1935	19	103	182	134	40	-66	19	-16	-41	-90	5	-6
1936	596	31	-70	-87	-66	-9	39	-12	-3	-60	-3	-16
1937	148	17	45	235	-108	22	-62	-32	1	-32	-19	-4
1938	7	126	152	55	-111	-32	54	4	-34	-29	28	-4
1939	489	-348	63	21	-69	27	-25	-40	-15	-13	-46	-24
1940	-5	110	8	-129	-18	-42	36	-36	-11	-40	-10	-22
1941	39	-5	-70	23	-36	-53	49	75	55	-24	-32	-52
1942	-3	148	1658	416	-69	119	69	12	10	-4	4	-44
1943	92	-21	51	223	-52	-12	5	-31	72	-99	6	-26
1944	116	223	210	483	165	175	54	-7	51	-174	-69	55
1945	420	59	-6	-15	-10	58	-59	3	17	-36	8	40
1946	131	138	88	59	58	75	71	88	98	-143	1	12
1947	214	140	-88	391	-200	-11	-58	-6	20	-99	65	111
1948	238	-11	42	70	-158	4	4	-143	54	-38	-38	10
1949	555	-15	183	-2	-108	-30	-4	63	8	-14	-72	36
1950	411	233	201	-34	33	31	10	30	1	-30	28	4
1951	145	103	75	229	54	20	59	104	97	4	53	121
1952	379	1346	111	102	35	3	-57	-34	-22	-64	-34	50
1953	615	226	567	172	238	205	94	184	29	-51	48	92
1954	92	-36	-11	156	-7	51	5	-27	0	-46	-43	13
1955	404	87	47	159	-1	122	111	140	-142	49	7	14
1956	52	66	89	67	-2	90	-9	-52	45	-44	-23	13
1957	77	111	223	205	76	-5	22	10	68	-26	-45	26
1958	149	180	44	14	37	-56	-26	35	-1	-13	14	2
1959	61	4	68	8	-3	-1	49	5	-15	39	-8	34
1960	750	375	107	87	1	59	1	61	-10	-5	39	45
1961	45	31	123	100	41	-1	5	-7	45	-38	29	25
1962	210	155	482	631	401	71	-53	-49	-4	57	27	164
1963	136	28	114	208	103	4	-39	21	-62	209	173	80
1964	11	191	190	199	57	54	-32	-39	25	177	137	118
1965	87	78	237	132	97	73	97	-21	-31	94	212	97
1966	593	163	94	139	119	171	83	71	30	130	51	86
1967	133	90	159	666	90	66	80	52	41	50	87	128
1968	72	244	94	356	100	85	55	-10	3	-34	216	60
1969	331	339	66	79	149	73	15	36	42	9	158	79

Location: Gavins Point Reservoir   Data: Adjusted Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	137	163	196	120	68	80	90	111	99	107	109	137
1931	125	129	105	78	64	70	66	85	77	103	79	135
1932	133	113	143	146	70	68	70	91	89	65	103	83
1933	151	105	131	66	72	90	72	87	97	79	107	97
1934	125	95	85	81	53	66	100	93	95	77	69	133
1935	125	147	119	133	73	64	68	83	95	77	79	79
1936	212	121	129	74	45	57	62	93	85	107	77	83
1937	79	111	60	66	86	82	154	93	54	91	81	93
1938	141	131	105	71	86	84	90	95	83	91	95	63
1939	155	131	71	58	83	94	84	105	89	83	79	93
1940	167	133	87	109	47	60	62	77	81	111	75	93
1941	131	117	85	89	80	66	74	97	91	83	85	91
1942	143	129	339	149	82	76	84	93	91	87	67	117
1943	137	117	99	139	72	64	64	83	93	77	89	87
1944	177	182	145	218	136	102	78	101	107	87	113	133
1945	214	139	115	173	90	110	80	99	97	64	107	123
1946	165	101	111	88	76	73	114	157	115	93	99	109
1947	173	159	115	488	170	33	154	107	40	34	60	97
1948	141	262	149	397	267	185	19	157	67	52	61	91
1949	438	240	222	153	142	55	162	139	79	16	94	55
1950	214	445	125	97	247	177	86	151	137	80	74	91
1951	178	291	229	263	92	273	255	151	106	76	89	164
1952	652	221	239	133	117	114	81	75	66	45	140	118
1953	334	125	166	75	12	-3	-43	-29	148	158	77	163
1954	165	104	130	241	-60	60	52	115	136	141	37	42
1955	274	82	70	58	25	-136	-29	-34	103	88	69	78
1956	178	55	-4	-119	-39	5	-7	164	165	128	71	126
1957	193	173	259	250	159	103	92	116	162	126	85	93
1958	162	230	126	138	176	113	64	93	132	74	61	101
1959	196	98	205	86	69	104	91	114	160	112	69	93
1960	446	361	290	128	82	119	107	114	139	92	74	161
1961	179	84	161	118	102	95	91	148	108	56	55	106
1962	448	206	272	424	465	178	144	147	160	99	91	153
1963	213	157	156	182	140	98	119	100	105	85	89	112
1964	134	200	174	220	137	124	110	102	112	45	78	89
1965	87	142	116	158	54	76	119	133	138	123	58	121
1966	265	156	116	125	81	112	83	76	114	29	124	90
1967	125	87	118	349	107	100	118	135	150	35	115	108
1968	134	164	134	158	126	79	99	146	137	39	106	82
1969	254	304	163	142	136	191	189	221	178	62	102	143

Location: Sioux City Data: Adjusted Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	74	67	148	95	32	20	20	12	18	0	12	16
1931	20	20	0	50	61	0	4	0	18	0	20	36
1932	262	100	67	95	116	61	56	12	4	0	10	10
1933	50	40	20	10	10	18	84	8	0	0	12	22
1934	14	18	0	65	28	24	14	0	14	8	6	8
1935	65	0	40	0	36	67	16	0	26	0	0	-8
1936	358	70	65	0	67	16	54	0	0	50	0	0
1937	124	198	134	54	116	166	30	8	38	10	2	67
1938	376	93	133	42	298	114	133	168	58	12	18	8
1939	0	274	0	16	145	67	32	0	2	20	0	0
1940	44	121	0	58	76	36	14	0	34	0	30	46
1941	164	94	56	0	140	6	34	84	94	14	6	0
1942	88	67	203	148	76	70	138	36	82	16	36	74
1943	0	0	279	67	116	147	0	0	10	0	2	106
1944	162	188	608	67	878	388	184	135	69	-2	6	80
1945	377	288	194	502	171	76	26	16	16	24	-4	84
1946	401	203	0	8	87	50	54	254	192	12	67	56
1947	20	458	300	185	36	99	44	54	121	-30	30	92
1948	408	558	190	171	196	137	74	125	117	58	8	48
1949	350	418	172	157	202	101	88	27	94	-29	-2	24
1950	450	-89	236	601	95	86	71	72	53	-74	-22	60
1951	297	739	410	581	580	241	297	152	4	34	-64	236
1952	373	1017	612	267	313	84	71	60	43	24	17	44
1953	317	198	346	140	-41	174	38	6	22	-20	21	124
1954	244	90	96	469	100	-1	-8	4	27	34	-11	-2
1955	268	-29	-84	-51	-57	-85	-86	-26	-39	21	31	-14
1956	44	57	36	41	35	25	-16	9	3	1	-34	35
1957	64	44	35	218	142	15	0	23	29	14	18	57
1958	56	83	37	13	28	-28	-28	-29	20	7	5	18
1959	65	73	131	75	4	2	-7	-17	-7	51	5	31
1960	189	1679	307	142	95	138	104	14	21	-6	-2	8
1961	329	89	146	147	75	94	62	44	62	-2	-5	41
1962	260	1677	311	810	504	167	62	47	31	13	40	40
1963	83	14	41	68	18	63	20	31	32	-9	68	41
1964	59	111	87	57	-8	48	68	41	53	9	59	42
1965	114	499	264	311	173	34	80	122	48	90	32	254
1966	277	183	149	139	36	54	62	71	48	83	5	94
1967	146	91	66	333	124	4	-14	-39	4	20	-10	49
1968	85	23	19	12	-32	-22	3	84	23	-96	-3	51
1969	119	1665	427	189	279	-4	-5	-16	-26	79	-35	101

Location: Omaha Data: Adjusted Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	216	36	72	0	54	0	60	0	65	12	16	6
1931	20	36	0	0	54	22	79	0	72	2	14	18
1932	76	41	14	7	18	9	72	1	58	-27	31	29
1933	80	94	-297	-308	134	70	-11	22	-17	-2	2	81
1934	-83	13	-213	57	196	31	17	-10	7	16	8	-6
1935	41	-9	49	-55	98	76	20	4	26	-14	-21	-11
1936	120	103	-28	-114	43	29	91	5	-40	45	-13	2
1937	114	36	50	-26	121	225	31	-19	6	-13	-22	39
1938	35	69	94	-239	-18	26	444	90	18	-9	5	5
1939	49	58	-42	19	134	75	45	10	2	29	-2	6
1940	25	32	-2	107	106	127	53	-47	34	16	41	83
1941	103	75	0	22	83	2	73	58	72	109	41	46
1942	142	67	224	301	317	123	27	11	-33	34	36	227
1943	-97	78	-11	83	417	149	84	26	42	-30	15	78
1944	325	-119	109	504	134	145	73	-1	38	-26	17	148
1945	352	268	382	407	215	322	30	16	13	28	78	169
1946	22	38	53	-127	-77	-5	-40	-66	36	62	21	39
1947	44	180	55	76	762	58	-15	-87	-6	-27	-18	249
1948	386	-188	-7	-138	116	98	28	-7	45	14	7	109
1949	276	551	40	76	44	74	-8	8	-35	18	38	36
1950	131	-113	132	217	145	100	55	26	71	57	113	82
1951	449	749	539	384	438	550	284	28	61	79	90	291
1952	161	105	124	97	277	19	26	39	118	54	-10	90
1953	144	206	55	355	238	97	17	-15	101	33	-89	26
1954	121	77	64	564	132	88	49	160	130	61	15	70
1955	131	197	42	54	184	-49	72	15	103	-25	13	24
1956	66	22	36	6	22	-8	-4	57	72	-24	-10	-4
1957	58	-57	28	271	55	-12	53	59	133	54	26	39
1958	108	31	-16	12	16	-7	-5	-11	87	-13	-27	-16
1959	57	-72	190	282	70	40	26	33	140	56	-25	54
1960	11	714	346	241	56	56	25	33	127	67	41	169
1961	533	120	22	139	-5	36	57	158	82	2	17	121
1962	701	493	296	353	411	147	271	83	87	69	47	104
1963	193	44	67	299	28	62	58	6	91	53	68	72
1964	-4	45	183	36	29	29	84	18	51	12	66	133
1965	472	932	189	133	48	27	124	79	57	31	26	217
1966	22	98	62	49	20	64	32	10	49	12	-14	26
1967	128	57	13	776	62	14	2	14	29	11	19	-24
1968	-29	6	13	70	7	32	45	118	7	74	-60	0
1969	353	914	219	249	392	55	100	52	47	47	38	120

Location: Nebraska City | Data: Adjusted Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	258	318	1155	426	315	312	437	306	335	278	287	392
1931	323	341	222	114	108	70	110	110	143	216	139	307
1932	689	318	211	682	212	403	157	169	175	69	220	149
1933	325	296	383	155	250	129	181	128	157	201	161	199
1934	216	179	79	113	61	61	98	102	147	76	70	206
1935	212	168	434	957	250	131	138	112	188	114	61	61
1936	686	205	224	106	61	61	88	64	91	85	5	140
1937	418	159	159	188	170	127	88	79	97	101	145	121
1938	294	194	280	150	227	127	217	105	118	145	138	104
1939	299	223	128	140	102	77	61	61	70	83	61	83
1940	255	130	136	283	61	97	61	61	100	62	159	285
1941	271	238	158	202	88	61	106	102	157	258	186	273
1942	408	161	493	663	268	100	255	98	224	127	124	403
1943	277	154	159	714	362	64	92	82	122	61	136	178
1944	515	841	1079	1308	506	197	112	89	110	76	151	360
1945	624	627	605	1046	508	147	70	123	225	112	171	350
1946	324	199	137	377	113	71	110	449	385	293	143	324
1947	429	397	250	1790	709	73	61	94	185	359	155	431
1948	1005	183	155	68	187	389	194	98	116	207	239	307
1949	1677	637	608	793	395	117	157	151	182	241	154	365
1950	718	376	789	307	666	348	83	196	167	150	150	269
1951	936	580	891	1244	652	433	418	412	392	348	346	550
1952	592	513	768	669	326	256	145	165	144	277	335	390
1953	551	427	675	453	219	82	61	92	148	222	164	409
1954	378	382	455	596	61	132	73	138	216	198	174	225
1955	478	129	120	249	83	62	61	119	136	71	159	218
1956	205	161	196	153	94	76	61	95	120	96	101	207
1957	285	298	315	730	344	146	165	218	214	248	147	265
1958	534	517	275	198	749	588	200	129	272	156	192	354
1959	566	410	909	458	262	395	121	249	283	240	157	359
1960	574	1583	1043	918	394	347	228	228	312	218	208	310
1961	523	423	432	455	170	123	134	264	279	189	187	297
1962	916	761	579	887	443	316	232	289	302	224	184	302
1963	733	365	283	417	143	151	225	210	268	102	222	299
1964	379	435	513	972	321	204	264	205	227	254	233	276
1965	795	684	818	772	618	168	788	723	453	408	250	460
1966	552	409	280	333	161	372	195	194	214	213	12	282
1967	276	240	188	2315	522	187	135	230	268	240	27	424
1968	333	307	250	267	157	156	151	352	353	262	154	290
1969	1087	682	409	426	470	108	121	340	302	335	148	459

Location: Kansas City　　　　　　　　　　Data: Adjusted Inflow (KAF/MONTH)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	240	260	1479	758	198	186	384	310	340	272	166	170
1931	220	280	252	252	301	248	415	466	1890	806	1124	750
1932	589	731	309	869	725	638	535	194	203	215	253	112
1933	54	416	189	54	209	208	311	134	54	127	58	73
1934	54	70	54	74	134	54	111	116	147	110	54	80
1935	115	54	1022	2951	1033	181	630	322	438	209	95	415
1936	847	341	700	322	148	54	215	134	54	54	54	518
1937	678	193	221	54	464	316	136	54	70	54	54	58
1938	54	281	938	604	296	437	332	197	124	89	54	105
1939	732	365	54	662	456	374	153	54	54	62	54	54
1940	211	54	227	149	172	368	198	65	89	54	178	270
1941	187	312	237	1941	398	292	1112	3201	1377	732	664	552
1942	864	766	1452	2082	956	718	1436	583	288	585	446	629
1943	133	303	780	3772	609	353	187	168	167	185	74	104
1944	863	3073	2740	715	1345	1624	1209	549	412	1197	433	542
1945	1620	3081	3867	2419	2064	771	267	373	269	90	448	356
1946	783	491	286	353	436	241	994	738	636	376	178	54
1947	559	2172	822	4488	1748	160	79	104	296	307	169	178
1948	2081	563	487	333	1312	931	244	54	262	268	651	1524
1949	1875	548	906	2888	1581	347	959	546	245	371	203	312
1950	54	54	1328	571	2480	1869	963	1357	408	217	270	378
1951	426	705	3119	4887	8555	3009	3455	1794	1098	349	372	488
1952	1470	878	1522	539	824	593	538	190	457	319	76	393
1953	109	323	273	54	182	54	93	98	289	86	54	73
1954	54	134	218	641	118	728	140	315	267	73	54	424
1955	361	271	170	402	295	54	54	89	282	54	59	54
1956	54	97	64	125	326	208	137	93	162	99	64	67
1957	54	210	422	1230	663	195	341	439	397	218	208	234
1958	1159	518	946	671	3300	1526	1701	615	599	264	161	559
1959	927	891	2012	1028	1060	472	674	1358	467	365	887	774
1960	1629	2815	1222	1227	979	642	590	305	316	290	139	372
1961	1494	1246	2072	1571	886	445	1884	1830	2203	631	677	2383
1962	1561	1044	891	1580	1122	468	710	614	455	357	155	384
1963	958	349	895	289	346	227	228	232	266	122	196	128
1964	58	394	526	1643	658	149	543	206	334	209	327	263
1965	1636	739	349	1820	3535	464	2026	1002	581	519	317	269
1966	397	324	362	685	175	222	261	159	276	144	148	142
1967	-6	398	216	4311	1233	464	583	976	462	365	346	286
1968	187	577	342	326	646	1477	370	782	531	576	460	910
1969	1835	2020	2134	1751	1937	568	553	557	523	527	69	211

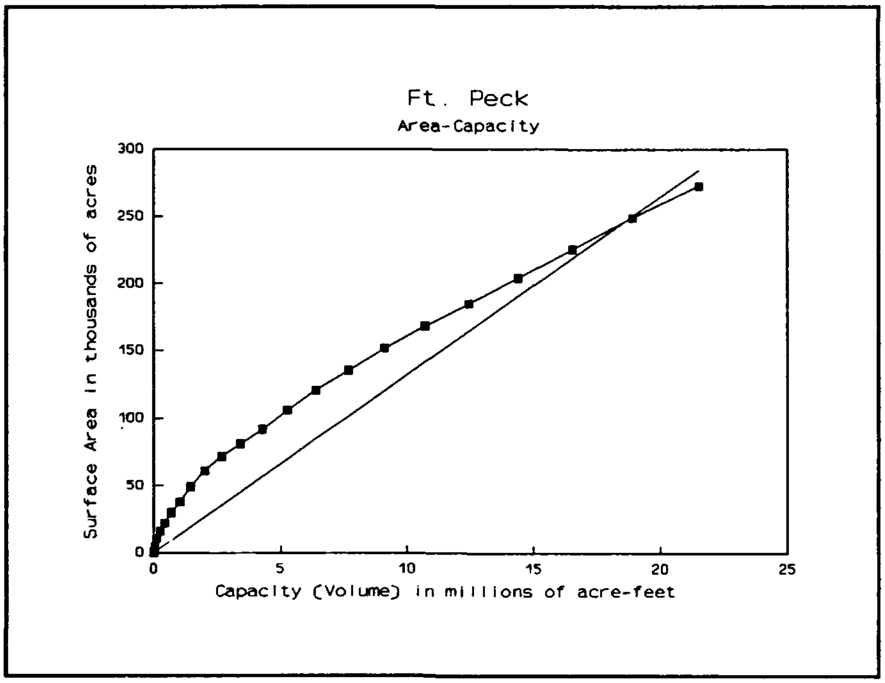
Location: Boonville　　　　Data: Adjusted Inflow (KAF/MONTH)

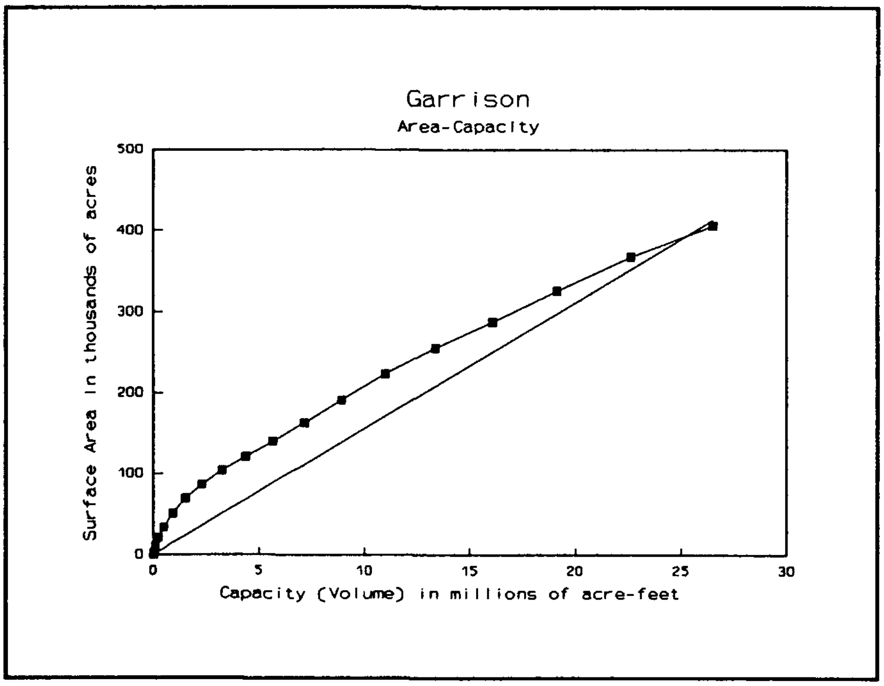
Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	216	153	442	279	192	50	70	40	40	140	30	36
1931	207	531	351	495	137	130	430	630	2260	1160	1490	217
1932	279	495	193	403	525	991	142	92	119	582	295	99
1933	90	401	556	67	262	211	123	246	30	109	30	32
1934	30	177	30	0	111	102	247	256	643	730	410	462
1935	509	193	2662	3763	1212	177	131	112	344	217	59	457
1936	615	190	196	130	116	57	249	436	90	75	373	2031
1937	917	302	895	30	477	288	126	30	54	30	39	30
1938	30	682	790	382	30	260	32	180	97	121	30	52
1939	621	955	92	793	359	389	105	34	30	42	30	30
1940	319	152	327	116	120	475	154	30	73	89	464	373
1941	85	240	103	400	285	37	133	1186	1197	632	376	1076
1942	959	900	841	1312	1364	119	346	312	427	815	346	409
1943	271	128	2572	2244	399	308	133	66	30	136	30	106
1944	857	3192	1478	30	30	345	305	229	124	587	32	395
1945	1223	2217	1552	1929	276	72	280	290	128	128	1642	207
1946	981	588	903	152	378	255	30	157	274	324	84	81
1947	882	2456	441	5365	2107	96	136	30	206	416	220	225
1948	1635	287	451	594	320	106	50	30	59	97	352	879
1949	452	535	182	752	585	167	316	326	129	311	613	589
1950	298	30	587	959	247	781	97	129	234	51	141	507
1951	494	1471	826	1007	4722	939	1215	351	710	562	499	443
1952	1853	526	1364	455	478	213	120	30	49	123	30	131
1953	373	1110	912	211	425	67	30	30	85	74	30	16
1954	122	102	204	338	30	82	37	276	139	30	357	534
1955	492	106	428	220	231	222	36	305	113	30	30	30
1956	-120	-52	-52	-44	278	157	-43	22	34	48	63	44
1957	30	202	337	74	352	102	168	244	199	470	127	255
1958	993	287	541	656	2116	1440	72	275	511	93	59	593
1959	1000	796	436	691	156	396	259	844	123	231	936	360
1960	77	2922	1872	608	1169	84	261	60	314	62	149	249
1961	1932	1684	1314	310	1019	380	2616	997	3408	528	639	2032
1962	1570	452	182	904	234	241	107	397	86	175	30	129
1963	775	30	454	94	161	52	30	30	33	48	45	52
1964	30	747	216	1067	322	30	416	30	129	213	1002	568
1965	1460	1604	287	346	1881	370	2065	420	218	310	289	154
1966	199	325	481	843	266	196	31	66	43	208	123	142
1967	121	1627	376	2662	1159	193	125	647	759	440	282	393
1968	98	849	604	250	248	423	108	87	288	268	490	752
1969	633	1403	965	1544	3658	226	717	1376	281	164	335	137

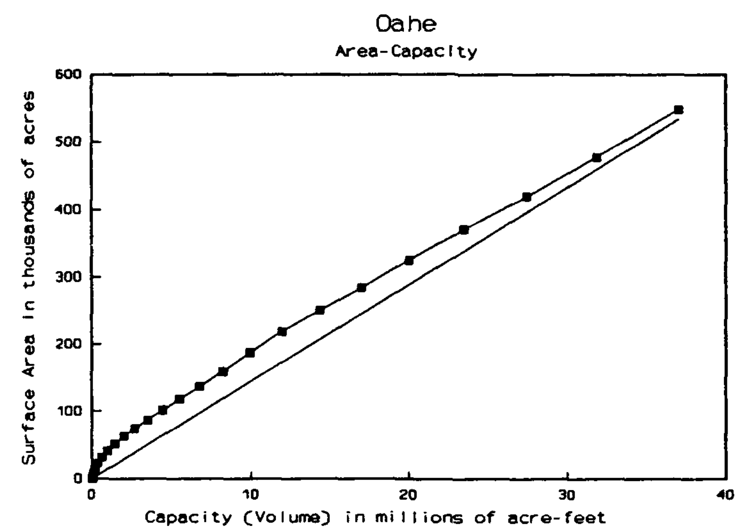
Location: Hermann Data: Adjusted Inflow (KAF/MONTH)

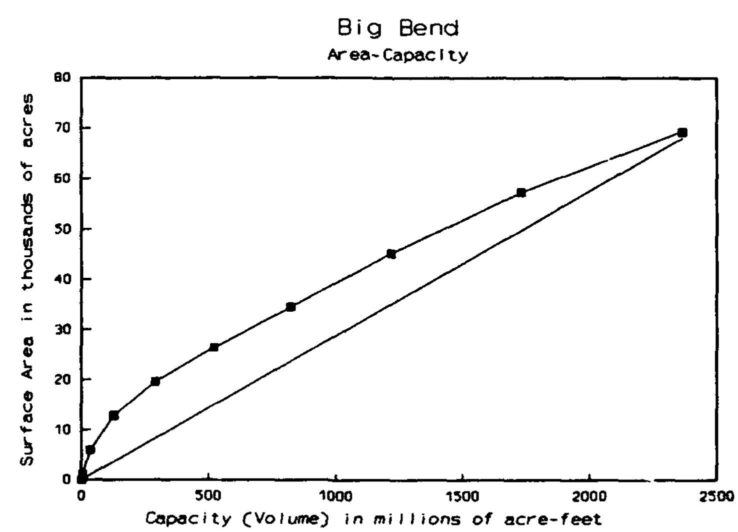
Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	399	150	412	607	334	206	553	120	135	382	97	195
1931	292	232	607	297	374	356	533	352	256	1322	1193	794
1932	450	329	20	67	1238	371	481	176	184	513	1143	663
1933	674	1030	2615	403	532	424	489	410	177	296	165	314
1934	516	361	163	160	312	425	866	422	437	1351	1313	727
1935	2034	960	1495	7335	1790	518	566	213	1173	978	284	393
1936	305	344	148	293	283	263	534	538	1066	449	2025	1673
1937	1139	1017	1932	2867	555	526	472	88	119	187	298	960
1938	718	2169	2992	2545	490	461	423	212	321	324	202	916
1939	1074	2006	1314	588	588	488	516	104	105	78	83	112
1940	446	490	510	705	316	410	601	106	127	190	1029	742
1941	127	2704	453	593	629	272	1234	4769	3633	1070	673	1387
1942	967	1690	1890	2744	2156	677	1163	516	786	2036	2205	614
1943	642	677	8347	3494	1087	683	437	309	289	358	317	463
1944	2406	2614	3496	500	589	1117	1241	781	223	660	374	692
1945	3287	5815	3018	3815	1774	624	1526	1319	401	278	1641	1311
1946	924	900	1648	473	509	1966	359	131	2796	997	484	319
1947	1092	4788	1667	1384	2553	598	566	286	416	307	663	216
1948	1570	944	693	2506	2991	1603	602	227	534	468	2265	2705
1949	2155	1444	1042	2480	1781	690	1314	1899	454	1075	2831	1166
1950	987	871	2340	2425	1594	1952	1548	384	503	317	164	1125
1951	2126	1692	1222	1487	9021	1063	4143	1465	2480	1306	1102	1670
1952	2057	1647	1073	429	468	558	349	88	64	193	235	350
1953	669	1173	1117	157	474	352	346	140	143	120	153	47
1954	25	130	313	376	243	92	293	391	250	437	851	1210
1955	1817	804	363	683	605	189	308	840	167	258	236	186
1956	61	88	364	409	391	194	182	45	63	182	196	364
1957	695	1798	2732	1579	1162	202	136	20	174	454	335	378
1958	2781	1320	940	830	3162	2486	913	285	379	383	487	1127
1959	994	543	601	498	373	266	60	1658	491	478	717	743
1960	1043	1863	2366	303	286	184	290	117	325	527	243	83
1961	1152	2442	6588	537	905	525	1778	675	2087	846	776	1363
1962	2374	1026	198	653	260	207	368	610	193	167	150	120
1963	770	288	1128	353	206	178	69	20	87	148	109	82
1964	180	1502	734	1705	545	182	126	91	180	222	464	373
1965	1048	2533	312	1708	1116	459	2752	1209	160	267	697	1301
1966	912	1694	1277	442	506	247	246	78	71	265	210	379
1967	128	773	1253	1760	2333	488	174	516	1650	1907	496	1504
1968	1089	1179	1661	1218	456	945	403	533	1446	1860	2243	2276
1969	1554	2408	1494	2108	3171	614	1054	3478	967	556	371	351

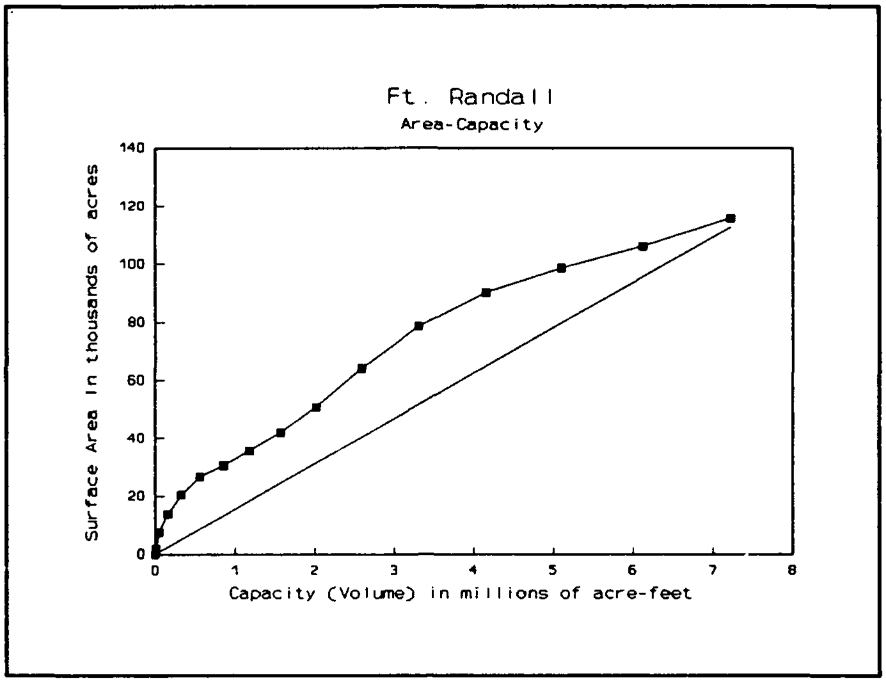
EXHIBIT D-4 RESERVOIR AREA-CAPACITY CURVES


Ft. Peck
Area-Capacity
Surface Area in thousands of acres
300
250
200
150
100
50
0
0
5
10
15
20
25
Capacity (Volume) in millions of acre-feet


Garrison
Area-Capacity
Surface Area in thousands of acres
500
400
300
200
100
0
0
5
10
15
20
25
30
Capacity (Volume) in millions of acre-feet


Oahe
Area-Capacity
Surface Area in thousands of acres
Capacity (Volume) in millions of acre-feet
0
100
200
300
400
500
600
10
20
30
40


Big Bend
Area-Capacity
Surface Area in thousands of acres
Capacity (Volume) in millions of acre-feet
0
10
20
30
40
50
60
70
80
500
1000
1500
2000
2500


Ft. Randall
Area-Capacity
Surface Area in thousands of acres
0
20
40
60
80
100
120
140
0
1
2
3
4
5
6
7
8
Capacity (Volume) in millions of acre-feet

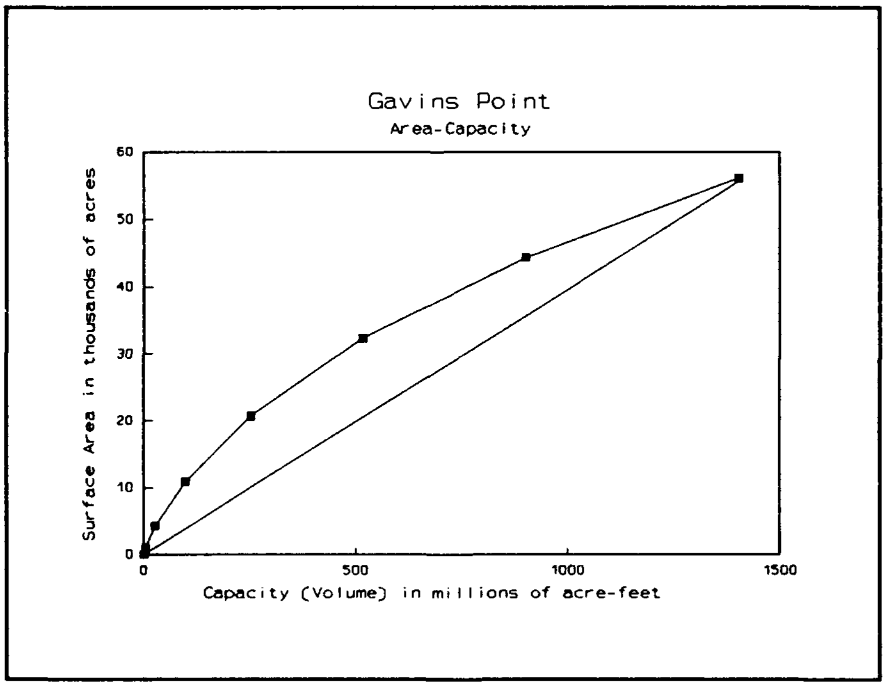

Gavins Point
Area-Capacity
Surface Area in thousands of acres
0
10
20
30
40
50
60
0
500
1000
1500
Capacity (Volume) in millions of acre-feet

EXHIBIT D-5 RESERVOIR ANNUAL EVAPORATION

Location: Fort Peck Reservoir Data: Evaporation Rate (Feet/Month)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	.000	.000	.153	.109	.414	.436	.414	.283	.262	.109	.000	.000
1931	.000	.000	.203	.145	.551	.580	.551	.377	.348	.145	.000	.000
1932	.000	.000	.158	.113	.429	.452	.429	.294	.271	.113	.000	.000
1933	.000	.000	.216	.154	.585	.616	.585	.400	.370	.154	.000	.000
1934	.000	.000	.239	.171	.650	.684	.650	.445	.410	.171	.000	.000
1935	.000	.000	.198	.141	.538	.566	.538	.368	.340	.141	.000	.000
1936	.000	.000	.336	.240	.912	.960	.912	.624	.576	.240	.000	.000
1937	.000	.000	.241	.172	.654	.688	.654	.447	.413	.172	.000	.000
1938	.000	.000	.132	.094	.359	.378	.359	.246	.227	.094	.000	.000
1939	.000	.000	.221	.157	.599	.630	.599	.410	.378	.157	.000	.000
1940	.000	.000	.147	.105	.399	.420	.399	.273	.252	.105	.000	.000
1941	.000	.000	.155	.111	.422	.444	.422	.289	.266	.111	.000	.000
1942	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1943	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1944	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1945	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1946	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1947	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1948	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1949	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1950	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1951	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1952	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1953	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1954	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1955	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1956	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1957	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1958	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1959	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1960	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1961	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1962	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1963	.000	.000	.161	.115	.437	.460	.437	.299	.276	.115	.000	.000
1964	.000	.000	.155	.111	.422	.444	.422	.289	.266	.111	.000	.000
1965	.000	.000	.155	.111	.422	.444	.422	.289	.266	.111	.000	.000
1966	.000	.000	.155	.111	.422	.444	.422	.289	.266	.111	.000	.000
1967	.000	.000	.148	.105	.401	.422	.401	.274	.253	.105	.000	.000
1968	.000	.000	.128	.091	.348	.366	.348	.238	.220	.091	.000	.000
1969	.000	.000	.147	.105	.399	.420	.399	.273	.252	.105	.000	.000

Location: Garrison Reservoir   Data: Evaporation Rate (Feet/Month)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	.000	.000	.169	.121	.460	.484	.460	.315	.290	.121	.000	.000
1931	.000	.000	.155	.111	.420	.442	.420	.287	.265	.111	.000	.000
1932	.000	.000	.141	.101	.384	.404	.384	.263	.242	.101	.000	.000
1933	.000	.000	.222	.159	.602	.634	.602	.412	.380	.159	.000	.000
1934	.000	.000	.262	.187	.711	.748	.711	.486	.449	.187	.000	.000
1935	.000	.000	.102	.072	.275	.290	.275	.189	.174	.072	.000	.000
1936	.000	.000	.293	.209	.796	.838	.796	.545	.503	.209	.000	.000
1937	.000	.000	.174	.124	.471	.496	.471	.322	.298	.124	.000	.000
1938	.000	.000	.127	.091	.346	.364	.346	.237	.218	.091	.000	.000
1939	.000	.000	.140	.100	.380	.400	.380	.260	.240	.100	.000	.000
1940	.000	.000	.122	.087	.331	.348	.331	.226	.209	.087	.000	.000
1941	.000	.000	.041	.029	.110	.116	.110	.075	.070	.029	.000	.000
1942	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1943	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1944	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1945	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1946	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1947	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1948	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1949	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1950	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1951	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1952	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1953	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1954	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1955	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1956	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1957	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1958	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1959	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1960	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1961	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1962	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1963	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1964	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1965	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1966	.000	.000	.125	.089	.340	.358	.340	.233	.215	.089	.000	.000
1967	.000	.000	.137	.098	.370	.390	.370	.254	.234	.098	.000	.000
1968	.000	.000	.103	.073	.279	.294	.279	.191	.176	.073	.000	.000
1969	.000	.000	.099	.070	.268	.282	.268	.183	.169	.070	.000	.000

Location: Oahe Reservoir   Data: Evaporation Rate (Feet/Month)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	.000	.000	.135	.096	.367	.386	.367	.251	.232	.096	.000	.000
1931	.000	.000	.195	.139	.530	.558	.530	.363	.335	.139	.000	.000
1932	.000	.000	.173	.123	.469	.494	.469	.321	.296	.123	.000	.000
1933	.000	.000	.269	.192	.730	.768	.730	.499	.461	.192	.000	.000
1934	.000	.000	.328	.234	.891	.938	.891	.610	.563	.234	.000	.000
1935	.000	.000	.184	.132	.500	.526	.500	.342	.316	.132	.000	.000
1936	.000	.000	.372	.265	1.009	1.062	1.009	.690	.637	.265	.000	.000
1937	.000	.000	.227	.162	.616	.648	.616	.421	.389	.162	.000	.000
1938	.000	.000	.223	.160	.606	.638	.606	.415	.383	.160	.000	.000
1939	.000	.000	.230	.164	.623	.656	.623	.426	.394	.164	.000	.000
1940	.000	.000	.204	.146	.555	.584	.555	.380	.350	.146	.000	.000
1941	.000	.000	.138	.098	.374	.394	.374	.256	.236	.098	.000	.000
1942	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1943	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1944	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1945	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1946	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1947	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1948	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1949	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1950	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1951	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1952	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1953	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1954	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1955	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1956	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1957	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1958	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1959	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1960	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1961	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1962	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1963	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1964	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1965	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1966	.000	.000	.113	.080	.306	.322	.306	.209	.193	.080	.000	.000
1967	.000	.000	.124	.089	.336	.354	.336	.230	.212	.089	.000	.000
1968	.000	.000	.102	.072	.275	.290	.275	.189	.174	.072	.000	.000
1969	.000	.000	.131	.093	.355	.374	.355	.243	.224	.093	.000	.000

Location: Fort Randall Reservoir Data: Evaporation Rate (Feet/Month)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	.000	.000	.167	.120	.454	.478	.454	.311	.287	.120	.000	.000
1931	.000	.000	.227	.162	.616	.648	.616	.421	.389	.162	.000	.000
1932	.000	.000	.204	.146	.555	.584	.555	.380	.350	.146	.000	.000
1933	.000	.000	.262	.188	.712	.750	.712	.487	.450	.188	.000	.000
1934	.000	.000	.323	.231	.878	.924	.878	.601	.554	.231	.000	.000
1935	.000	.000	.221	.158	.600	.632	.600	.411	.379	.158	.000	.000
1936	.000	.000	.354	.253	.961	1.012	.961	.658	.607	.253	.000	.000
1937	.000	.000	.260	.186	.707	.744	.707	.484	.446	.186	.000	.000
1938	.000	.000	.218	.155	.591	.622	.591	.404	.373	.155	.000	.000
1939	.000	.000	.242	.172	.655	.690	.655	.449	.414	.172	.000	.000
1940	.000	.000	.256	.183	.695	.732	.695	.476	.439	.183	.000	.000
1941	.000	.000	.160	.114	.433	.456	.433	.296	.274	.114	.000	.000
1942	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1943	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1944	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1945	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1946	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1947	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1948	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1949	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1950	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1951	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1952	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1953	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1954	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1955	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1956	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1957	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1958	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1959	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1960	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1961	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1962	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1963	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1964	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1965	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1966	.000	.000	.106	.075	.287	.302	.287	.196	.181	.075	.000	.000
1967	.000	.000	.102	.073	.277	.292	.277	.190	.175	.073	.000	.000
1968	.000	.000	.088	.063	.239	.252	.239	.164	.151	.063	.000	.000
1969	.000	.000	.119	.085	.323	.340	.323	.221	.204	.085	.000	.000

Location: Gavins Point Reservoir Data: Evaporation Rate (Feet/Month)

Year	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB
1930	.000	.000	.122	.087	.332	.350	.332	.227	.210	.087	.000	.000
1931	.000	.000	.175	.125	.475	.500	.475	.325	.300	.125	.000	.000
1932	.000	.000	.192	.138	.522	.550	.522	.357	.330	.138	.000	.000
1933	.000	.000	.245	.175	.665	.700	.665	.455	.420	.175	.000	.000
1934	.000	.000	.280	.200	.760	.800	.760	.520	.480	.200	.000	.000
1935	.000	.000	.105	.075	.285	.300	.285	.195	.180	.075	.000	.000
1936	.000	.000	.217	.155	.589	.620	.589	.403	.372	.155	.000	.000
1937	.000	.000	.140	.100	.380	.400	.380	.260	.240	.100	.000	.000
1938	.000	.000	.126	.090	.342	.360	.342	.234	.216	.090	.000	.000
1939	.000	.000	.175	.125	.475	.500	.475	.325	.300	.125	.000	.000
1940	.000	.000	.210	.150	.570	.600	.570	.390	.360	.150	.000	.000
1941	.000	.000	.105	.075	.285	.300	.285	.195	.180	.075	.000	.000
1942	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1943	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1944	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1945	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1946	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1947	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1948	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1949	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1950	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1951	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1952	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1953	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1954	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1955	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1956	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1957	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1958	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1959	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1960	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1961	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1962	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1963	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1964	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1965	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1966	.000	.000	.082	.058	.222	.234	.222	.152	.140	.058	.000	.000
1967	.000	.000	.137	.098	.370	.390	.370	.254	.234	.098	.000	.000
1968	.000	.000	.147	.105	.399	.420	.399	.273	.252	.105	.000	.000
1969	.000	.000	.092	.065	.249	.262	.249	.170	.157	.065	.000	.000

APPENDIX E

PENALTY FUNCTIONS USED IN PHASE I ANALYSIS

APPENDIX E

PENALTY FUNCTIONS USED IN PHASE I ANALYSIS

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APPENDIX E

PENALTY FUNCTIONS USED IN PHASE I ANALYSIS

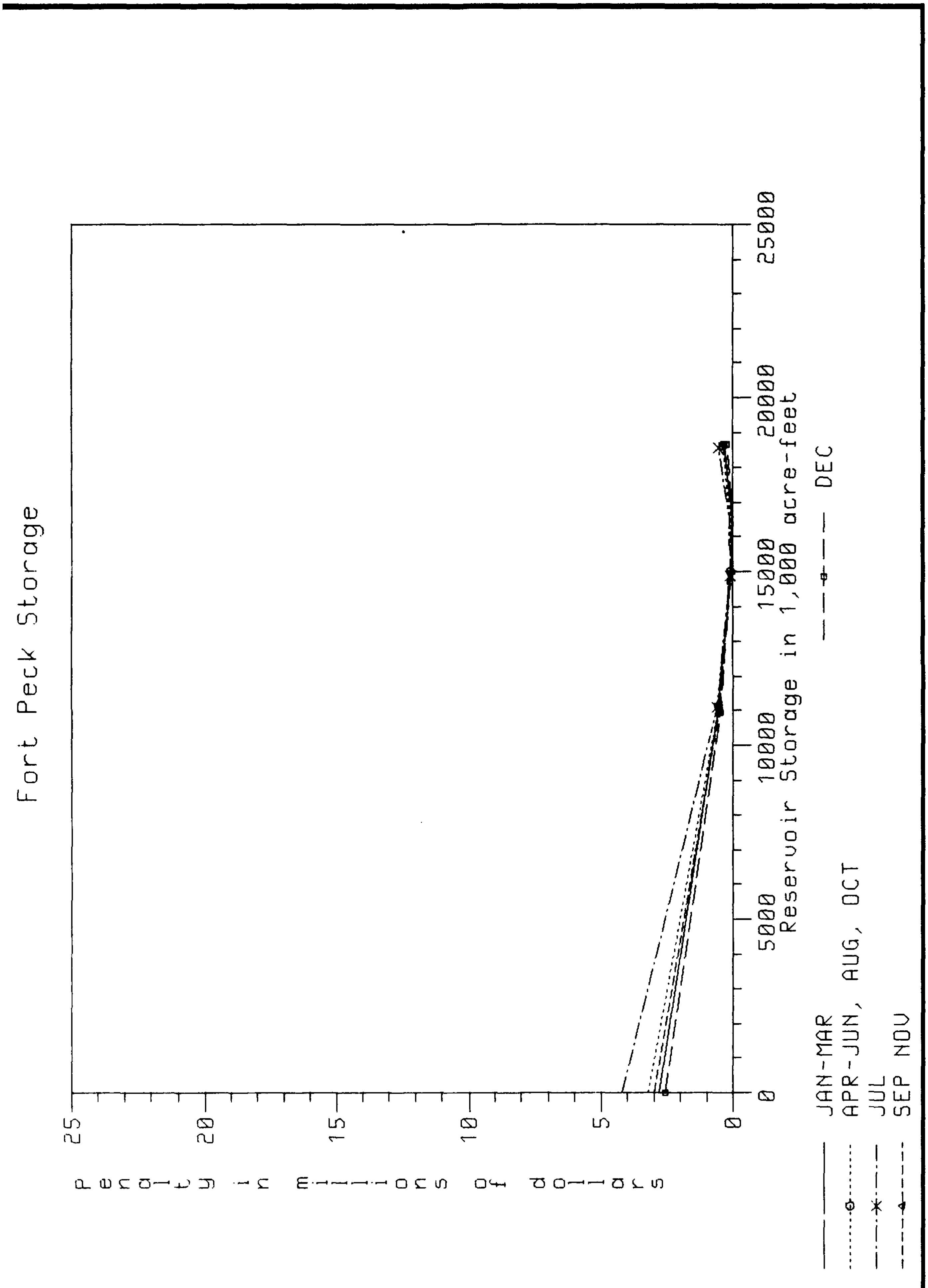
INTRODUCTION

The following plots depict the edited penalty functions used in Phase I of the study. The penalties are in millions of dollars and the storage or flow in 1,000 acre-feet per month. These edited composite penalty functions were derived by combining the original individual penalty functions supplied by IWR and then manually editing the computed function. Appendix E contains the convex, composite functions used as input to HEC-PRM.

From the standpoint of network flow programming, the reservoir storage arcs contain flow volume per month. The beginning-of-period storage comes into a node through arcs connected to the same node in the previous time period and the end-of-period storage leaves the node through arcs connected to the same node in the next time period.

The graphs are plotted on 3 scales: (1) reservoir storage, penalty from 0 to $25 million, storage from 0 to 25 million acre-feet per month; (2) reservoir release, penalty from 0 to $10 million, release from 0 to 7 million acre-feet per month; (3) channel flow, penalty from 0 to $20 million, flow from 0 to 20 million acre-feet per month.

For each reservoir, there are actually 2 reservoir release links: (1) a hydropower energy release link, and (2) all other functions release link. The hydropower energy function was separated to facilitate an iterative solution to the non-linear energy penalty function. The hydropower energy penalty is a function of both head and discharge. In Phase I, it was assumed that head was constant for all releases. The most conservative (lowest head) energy function was selected and is plotted on the reservoir release link penalty function in this appendix. They are plotted with the "all other" reservoir release penalty functions even though energy is treated as a separate link.



GURE E-1 Ft. Peck

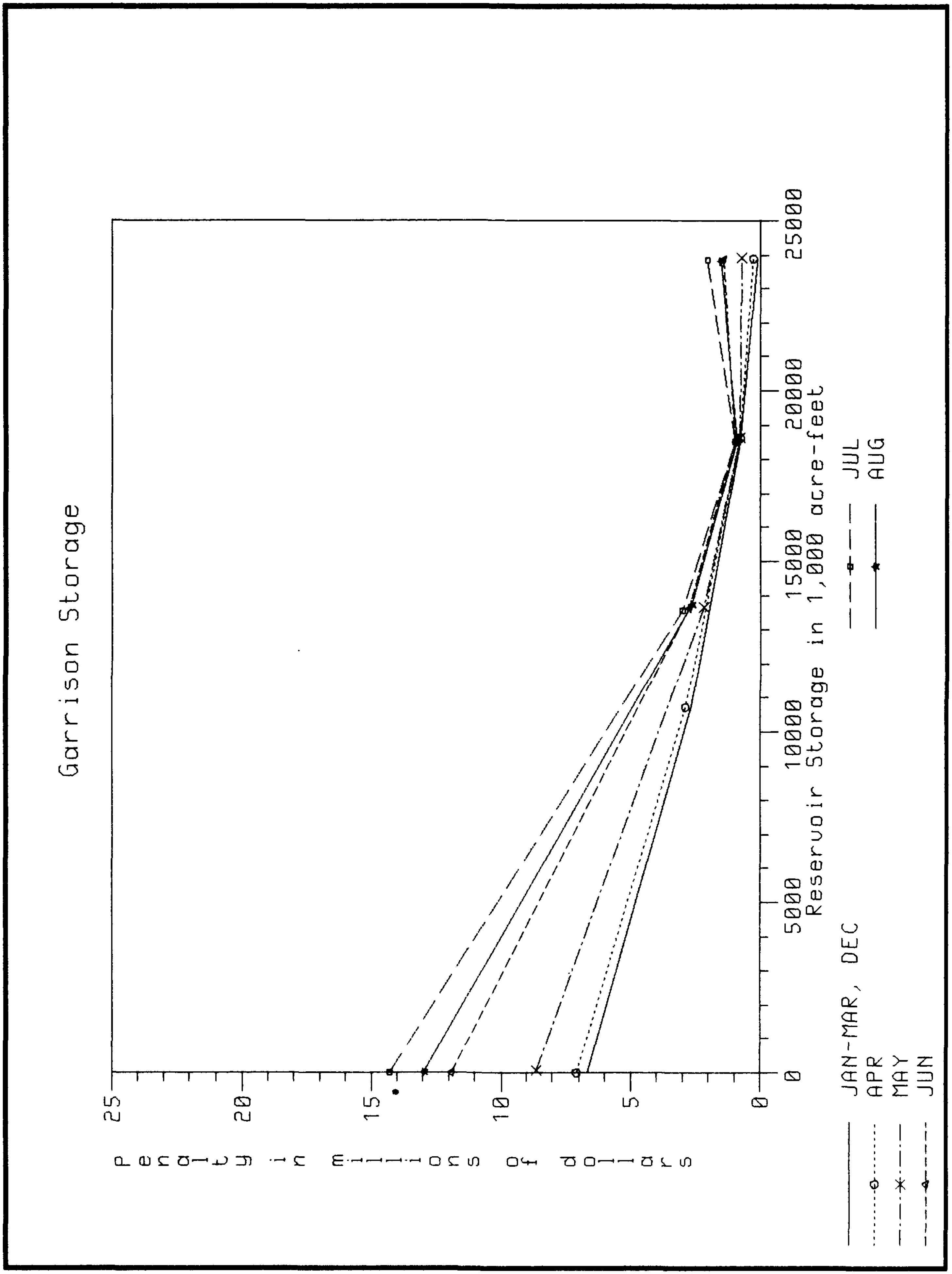
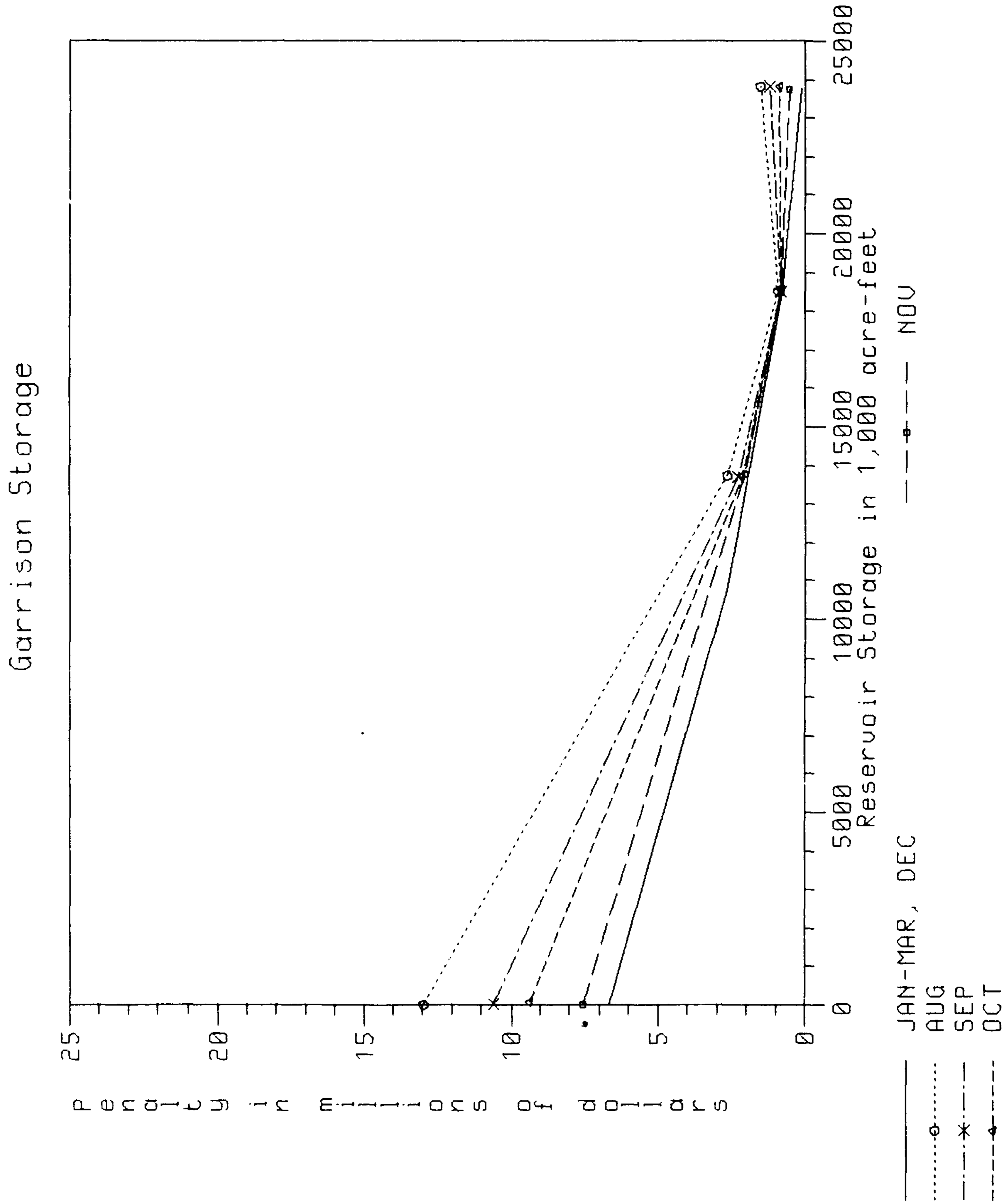


FIGURE E-2 Garrison



GURE E-2 Garrison (continued)

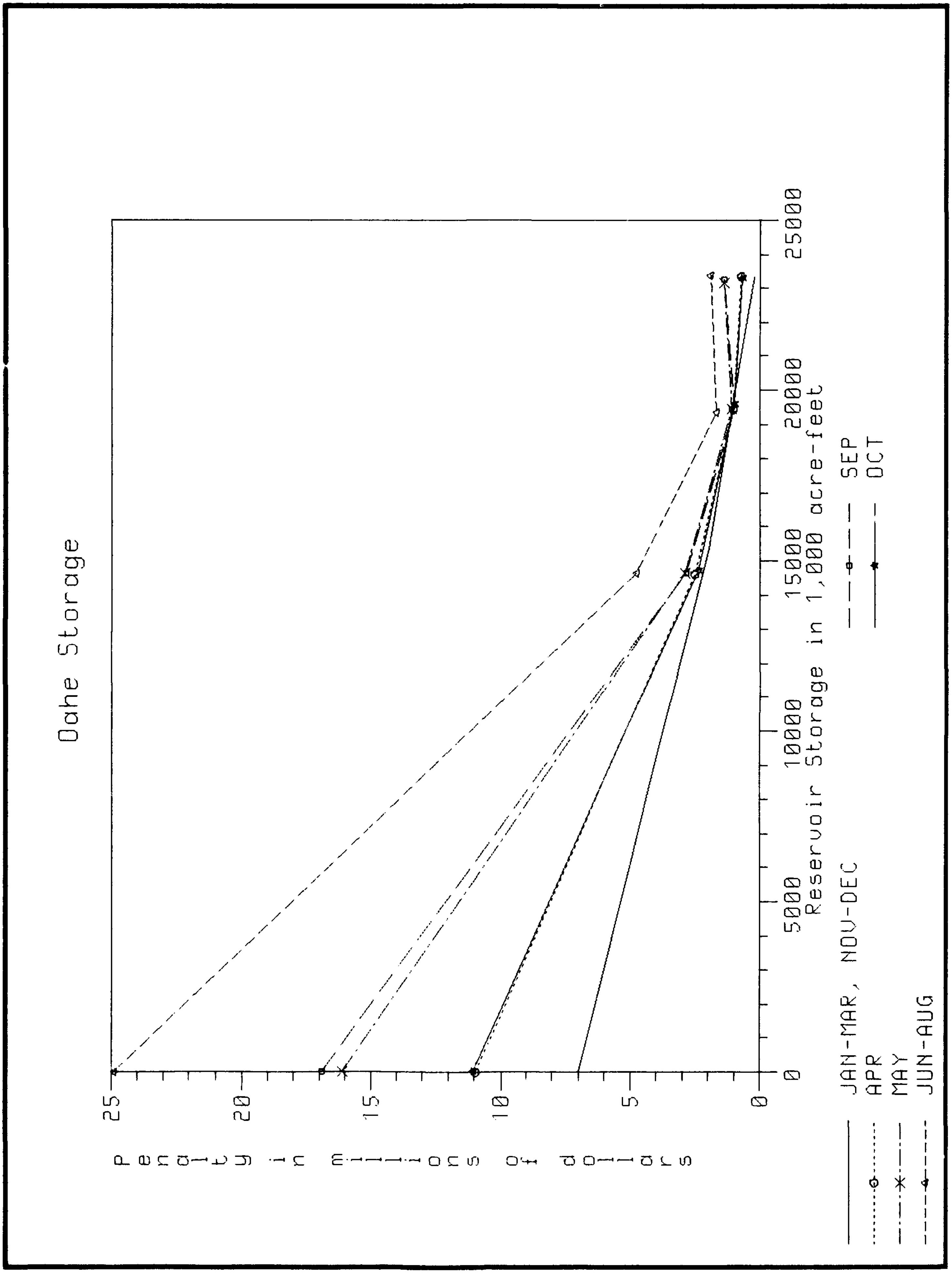


FIGURE E-3 Oahe

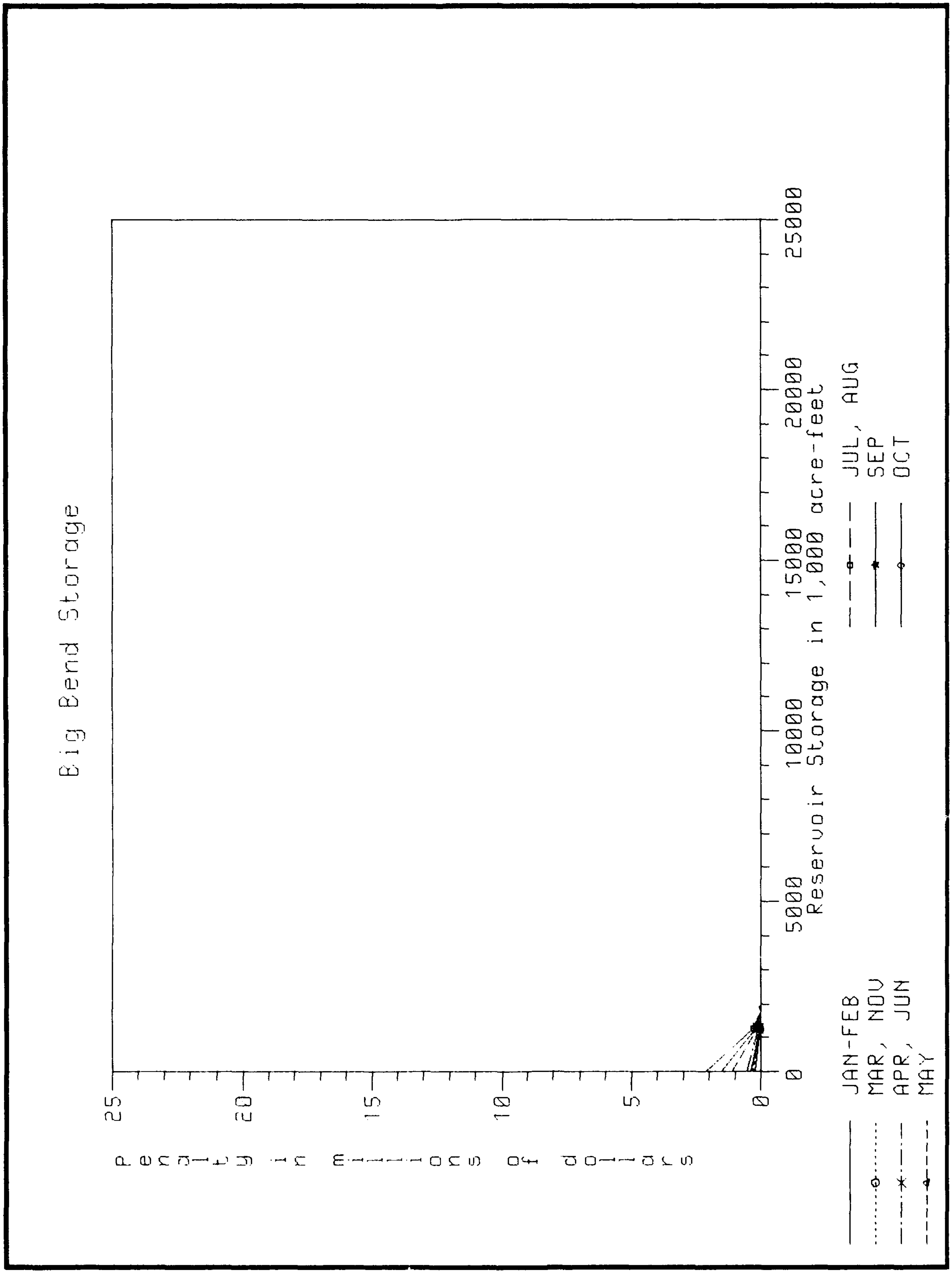


FIGURE E-4 Big Bend

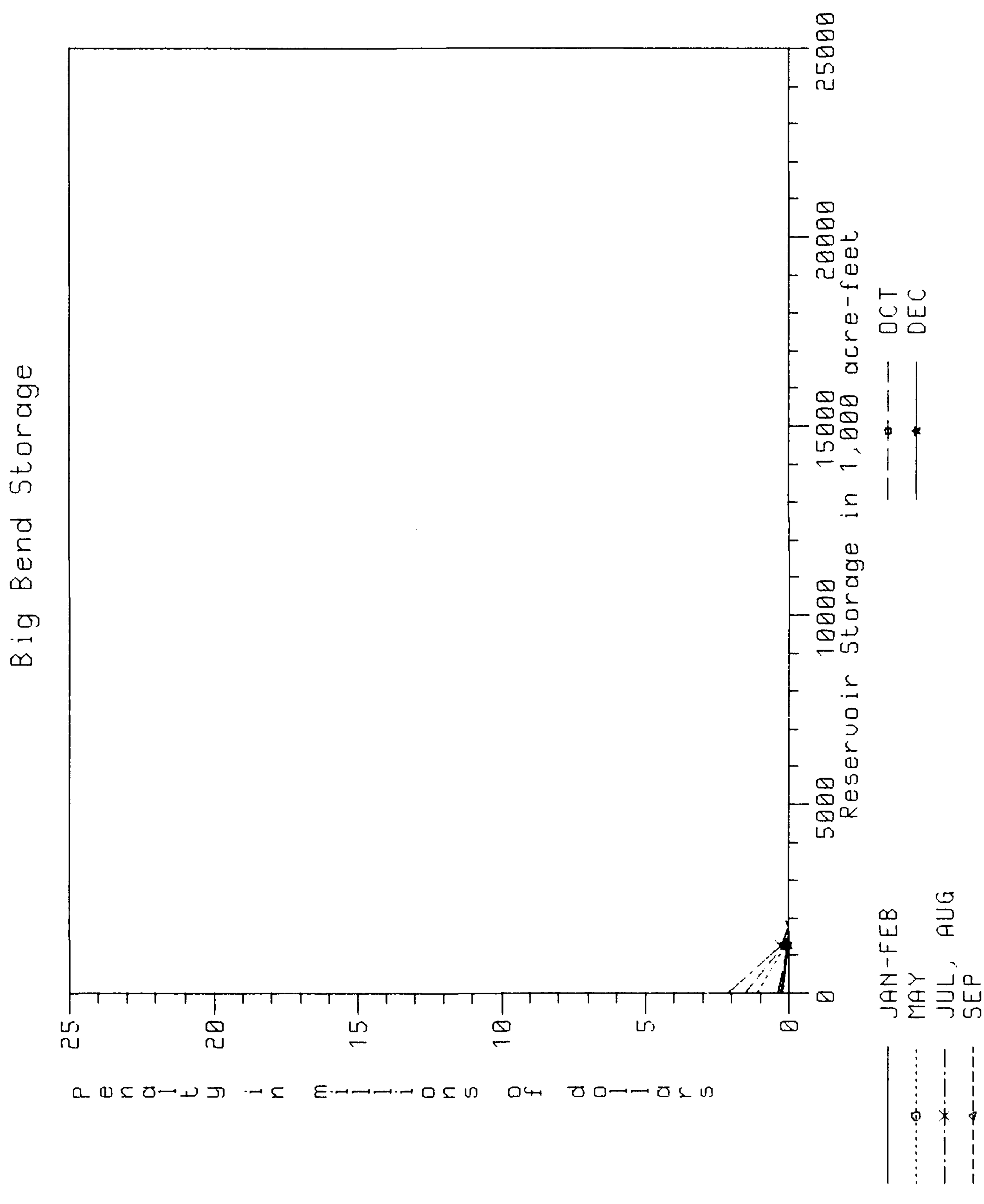


FIGURE E-4 Big Bend (continued)

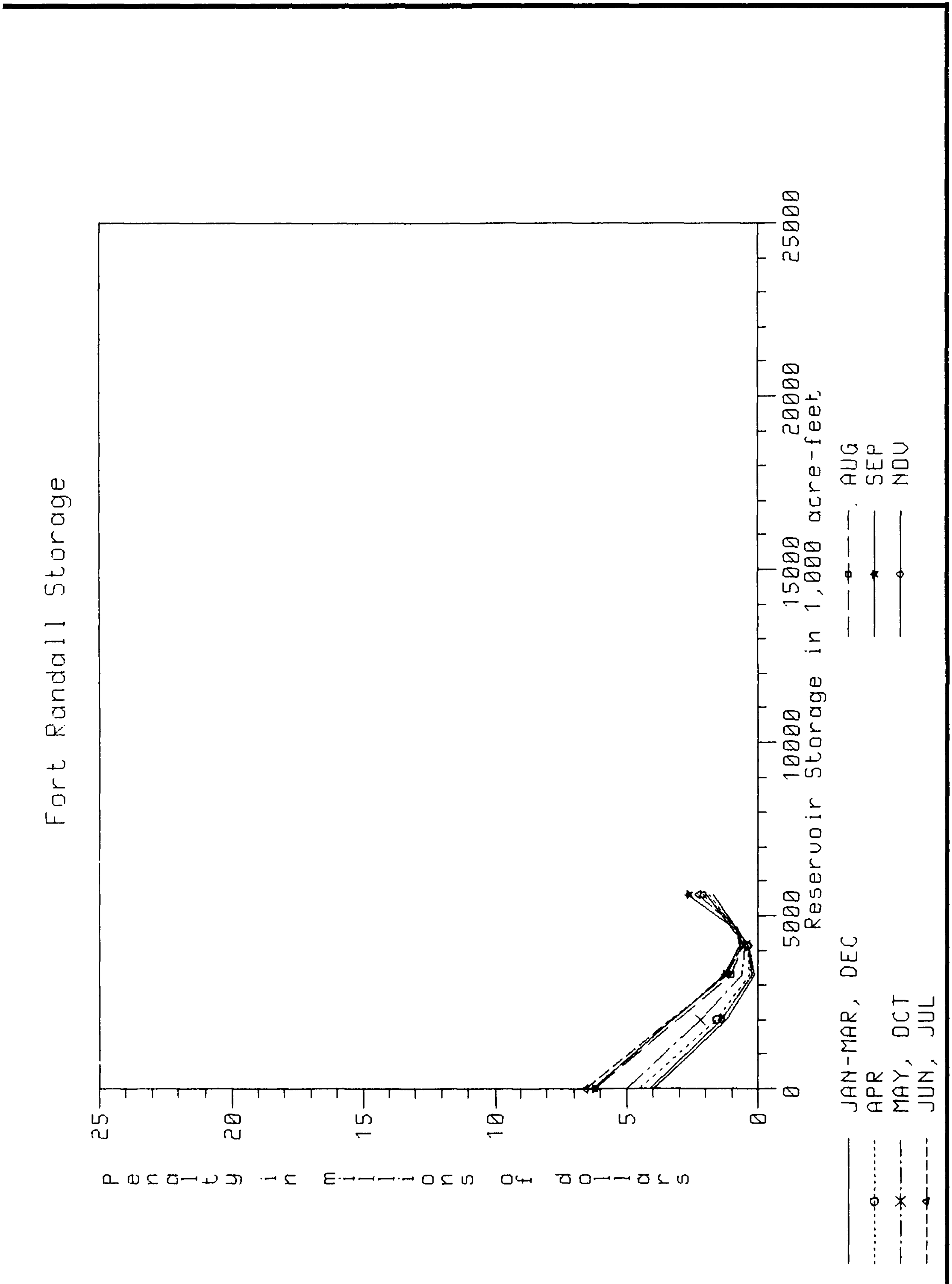


FIGURE E-5 Ft. Randall

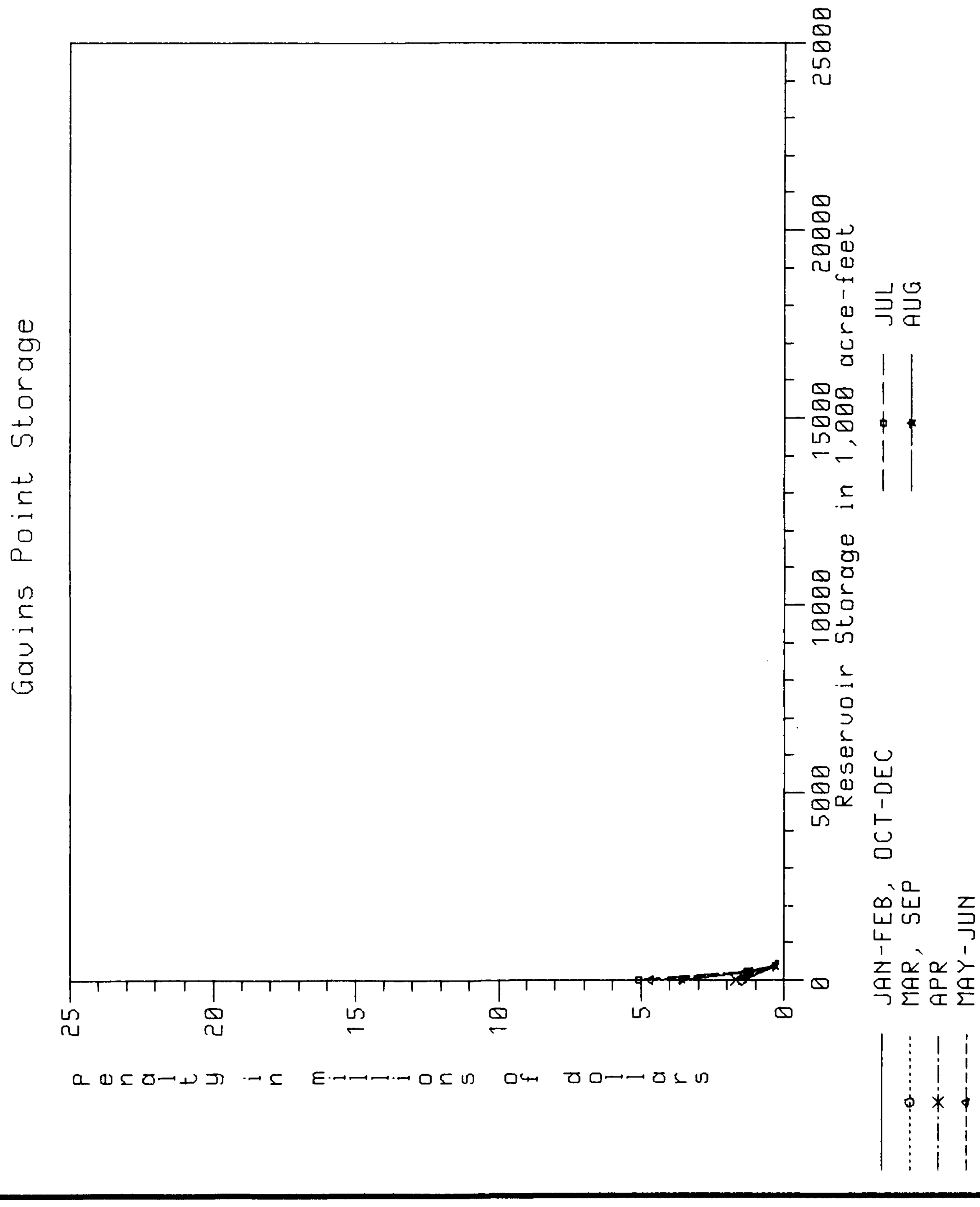


FIGURE E-6 Gavins Point

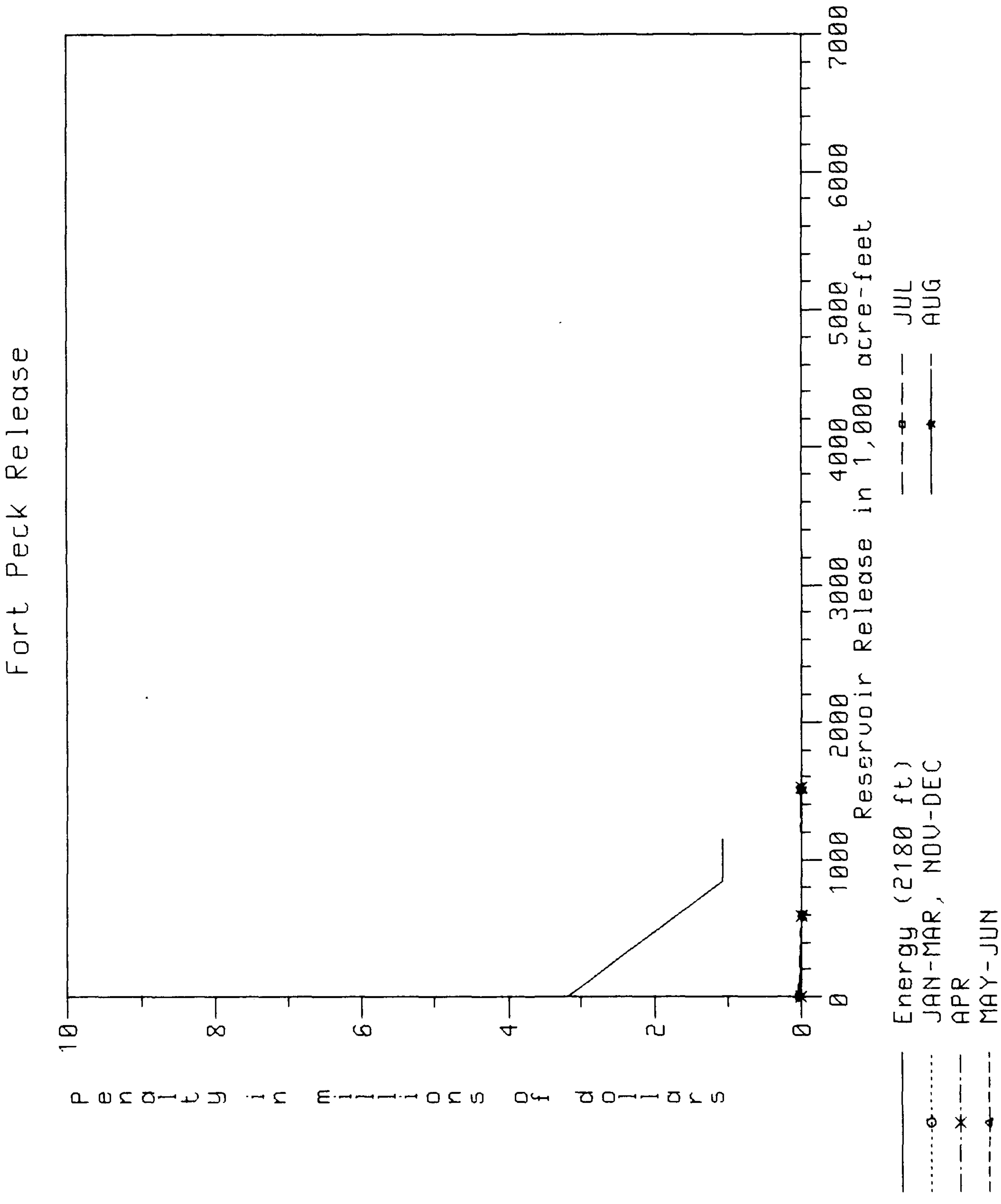


FIGURE E-7 Ft. Peck to Garrison

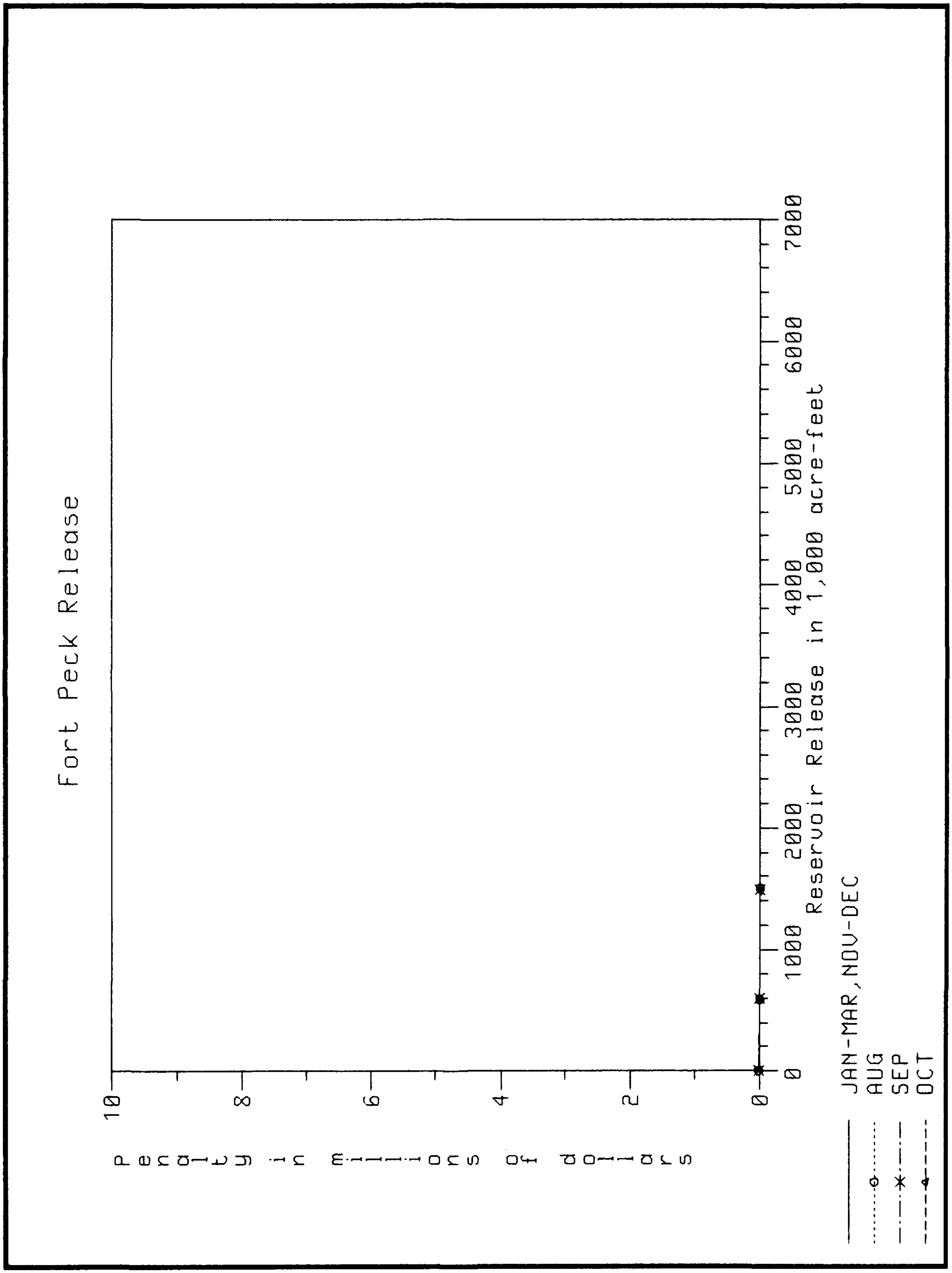


FIGURE E-7 Ft. Peck to Garrison (continued)

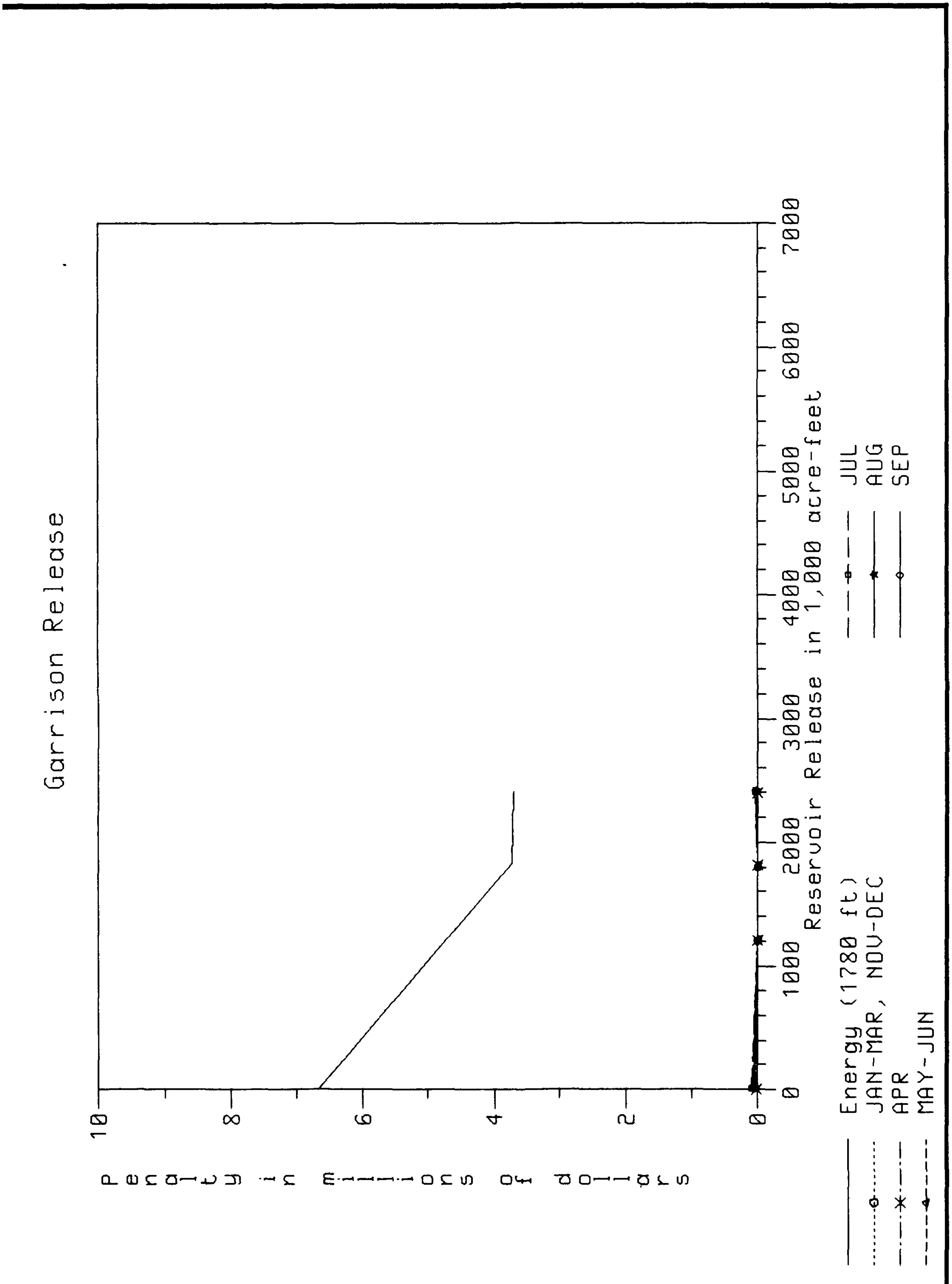


FIGURE E-8 Garrison to Oahe

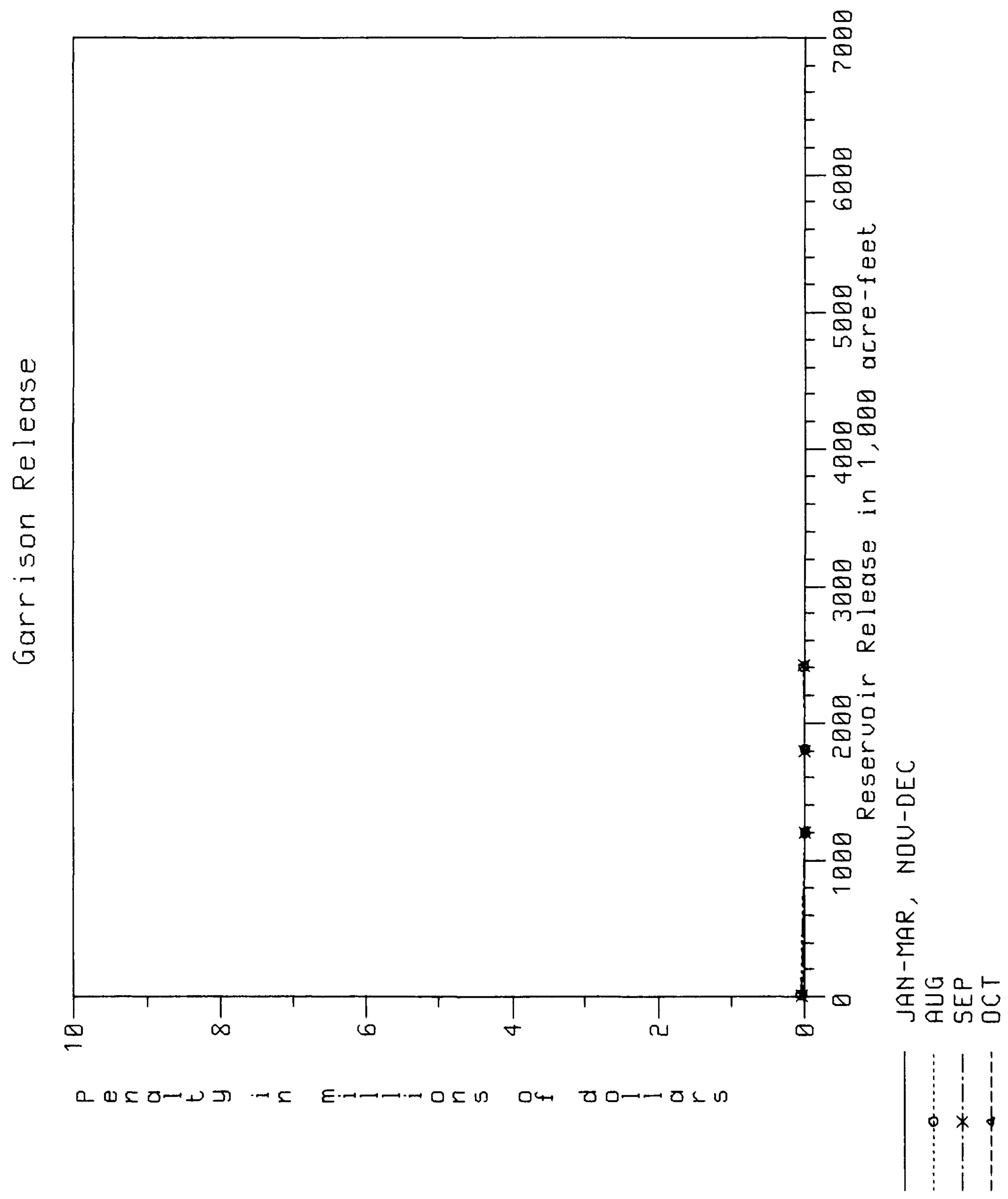
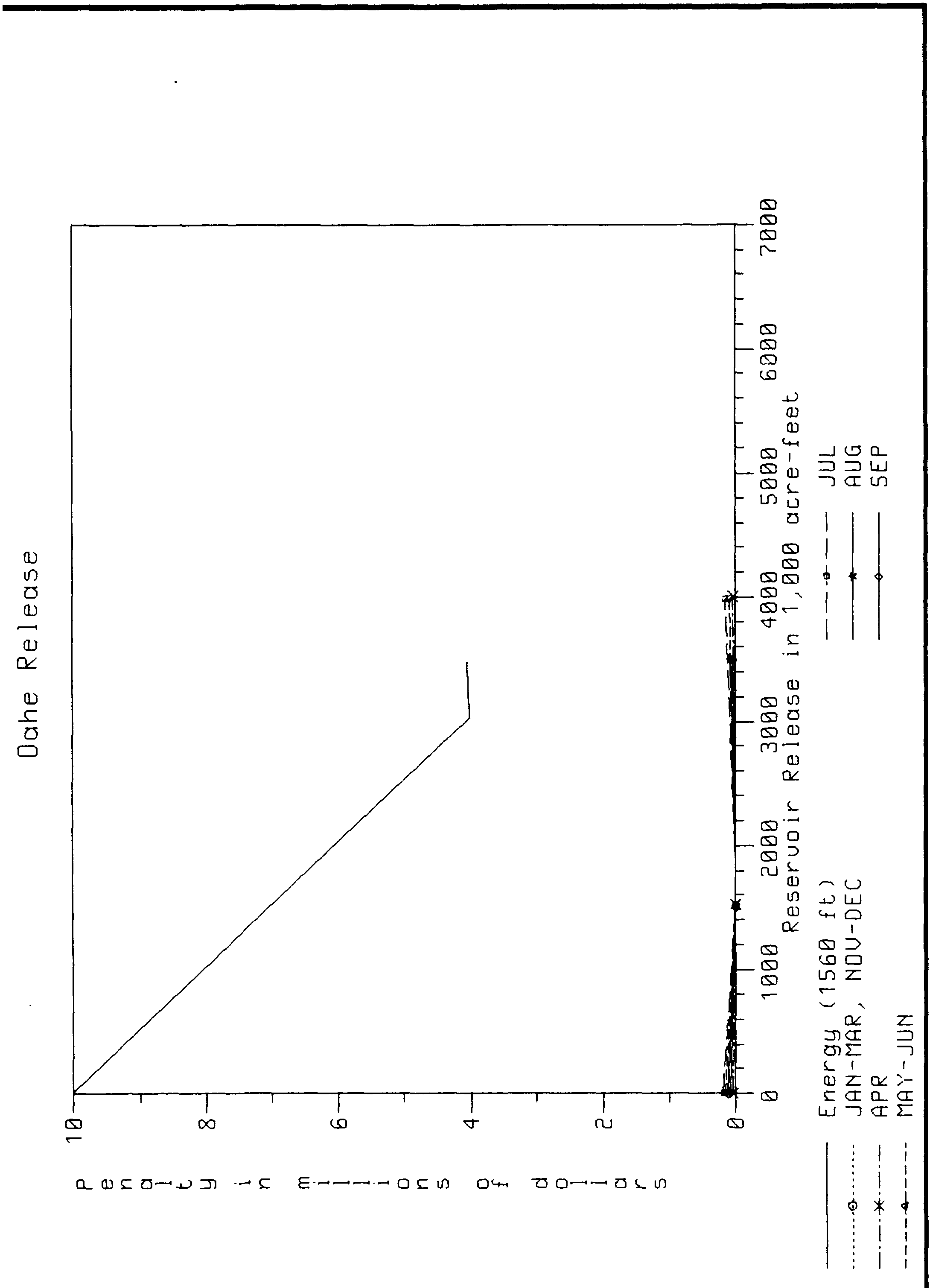


FIGURE E-8 Garrison to Oahe (continued)



GURE E-9 Oahe to Big Bend

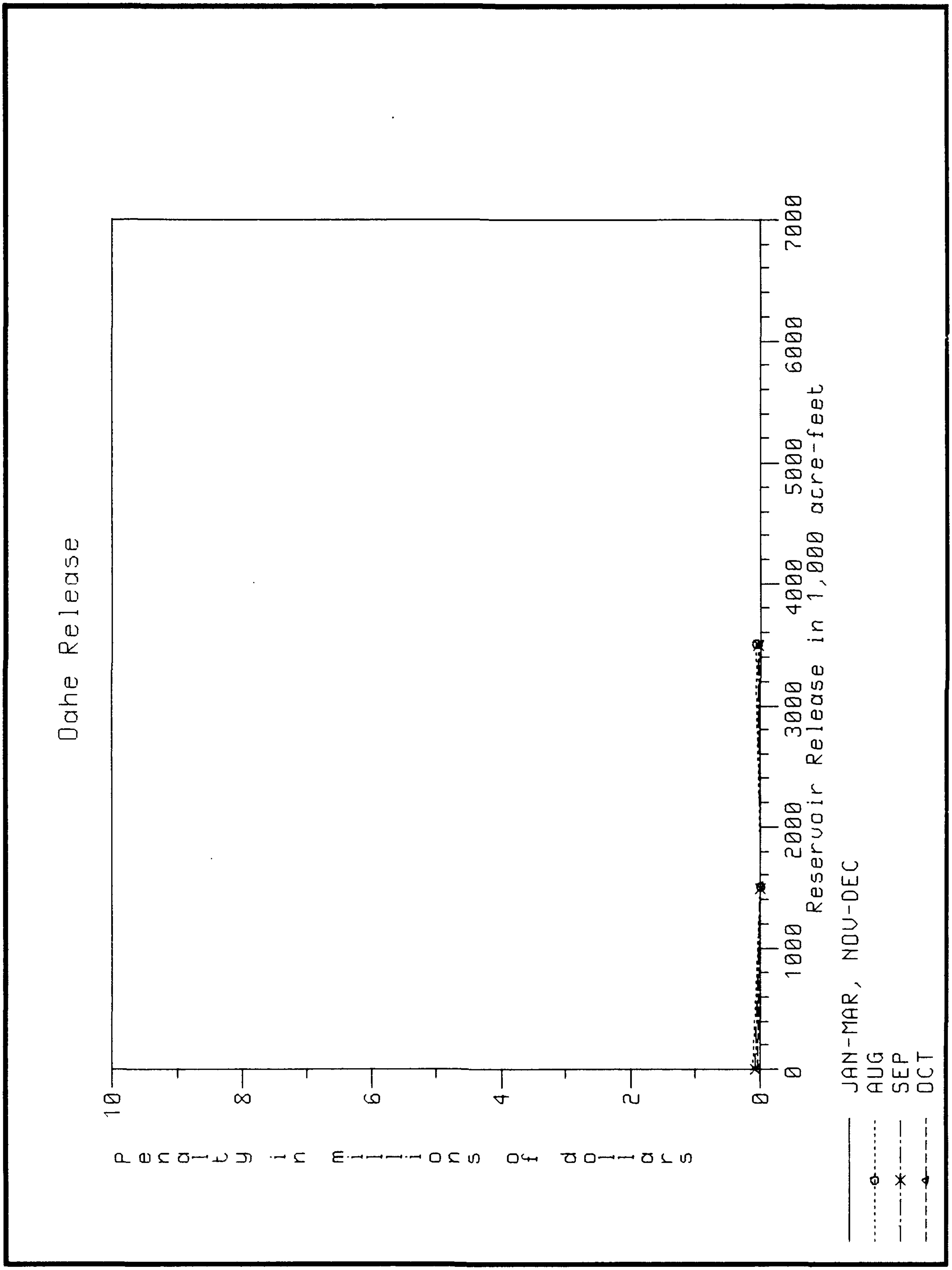
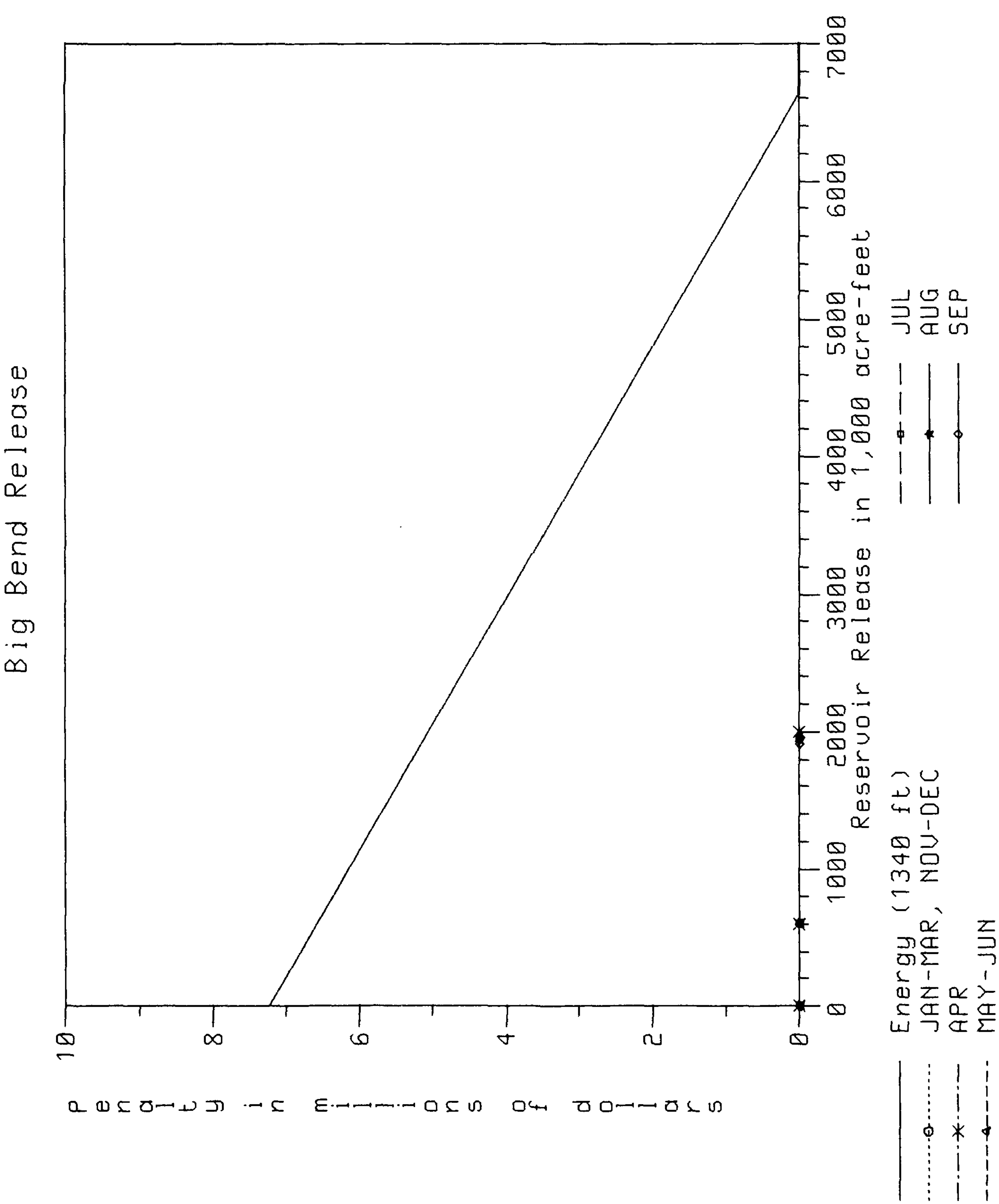


FIGURE E-9 Oahe to Big Bend (continued)



GURE E-10 Big Bend to Ft. Randall

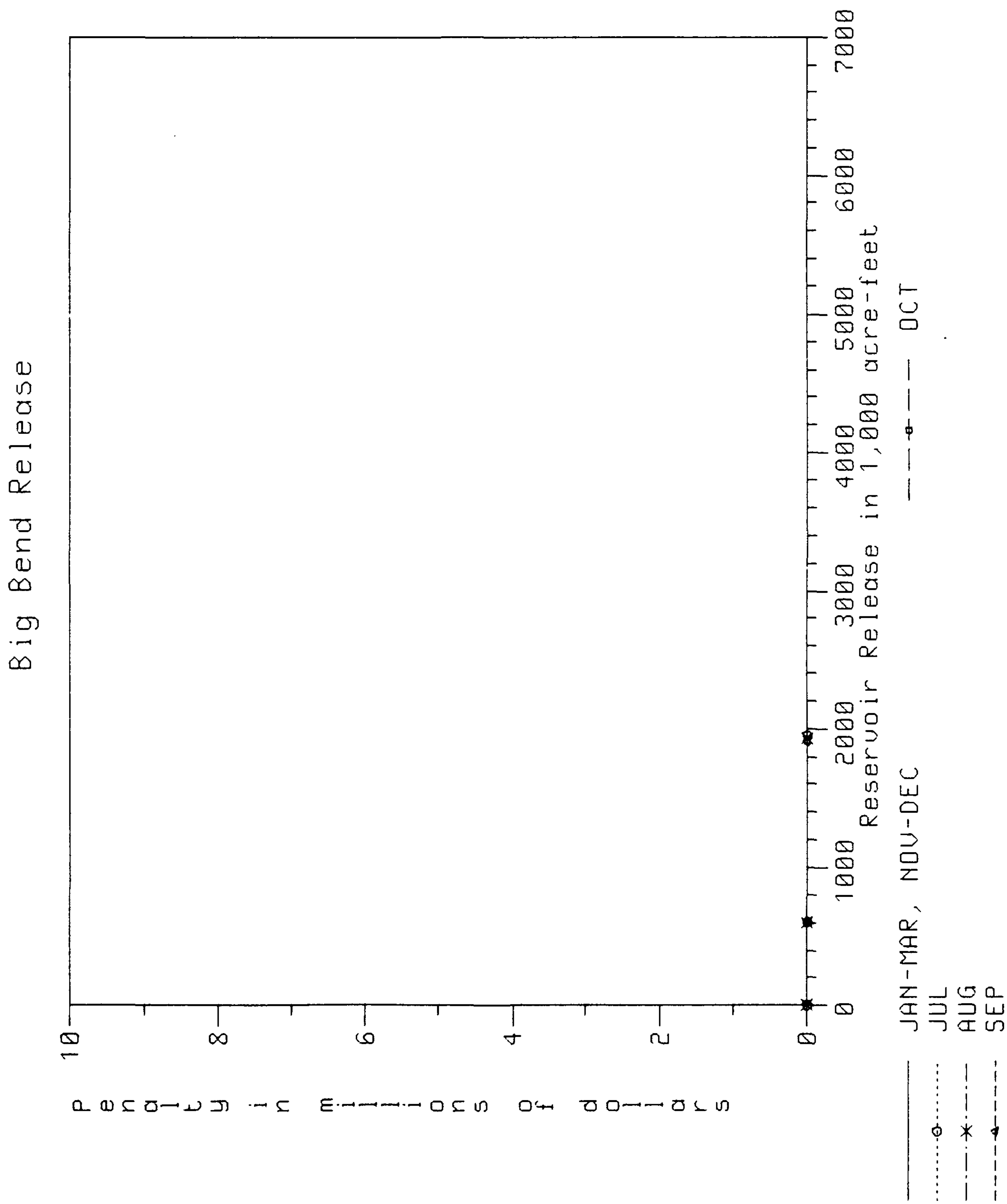
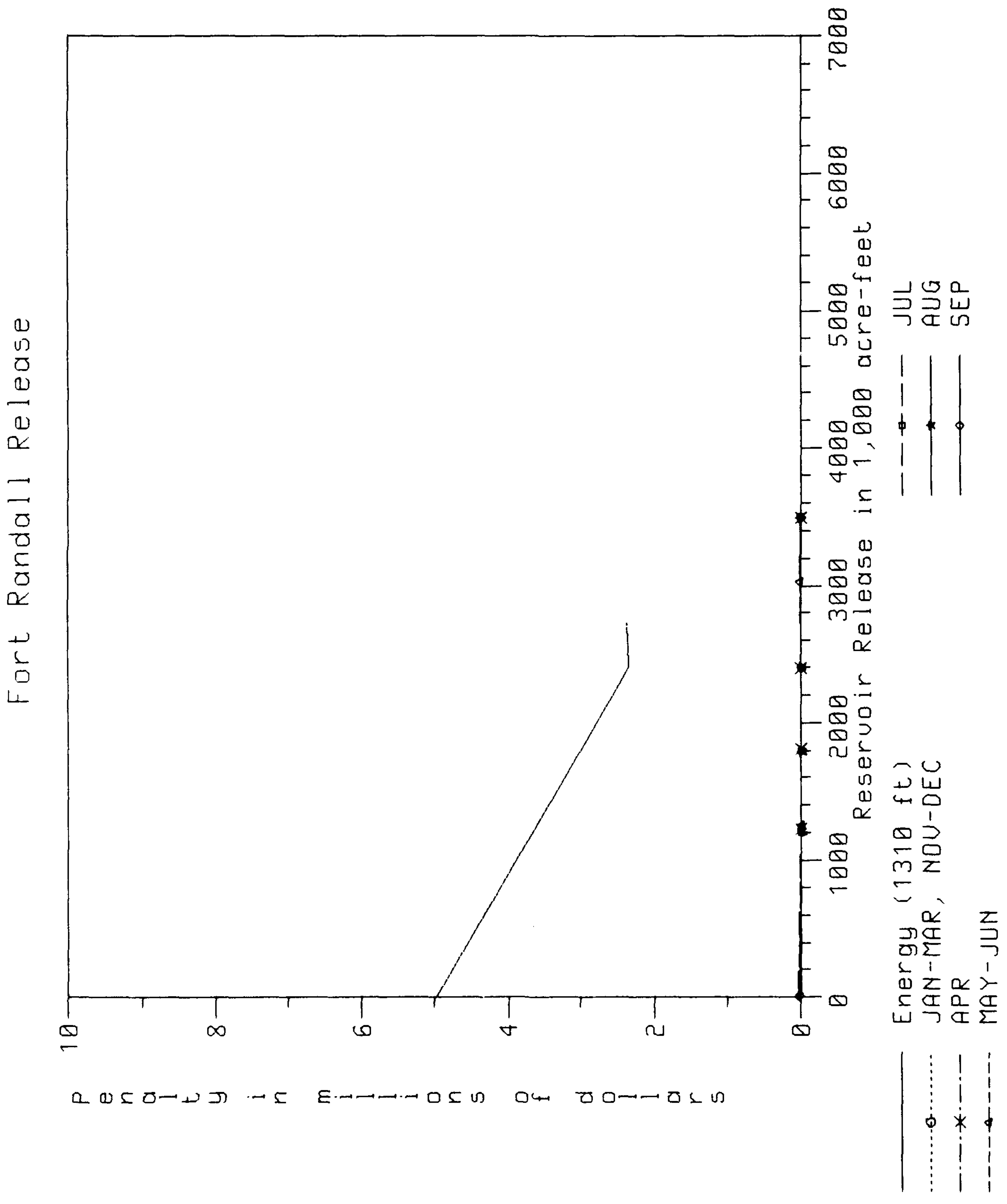


FIGURE E-10 Big Bend to Ft. Randall (continued)



IGURE E-11 Ft. Randall to Gavins Point

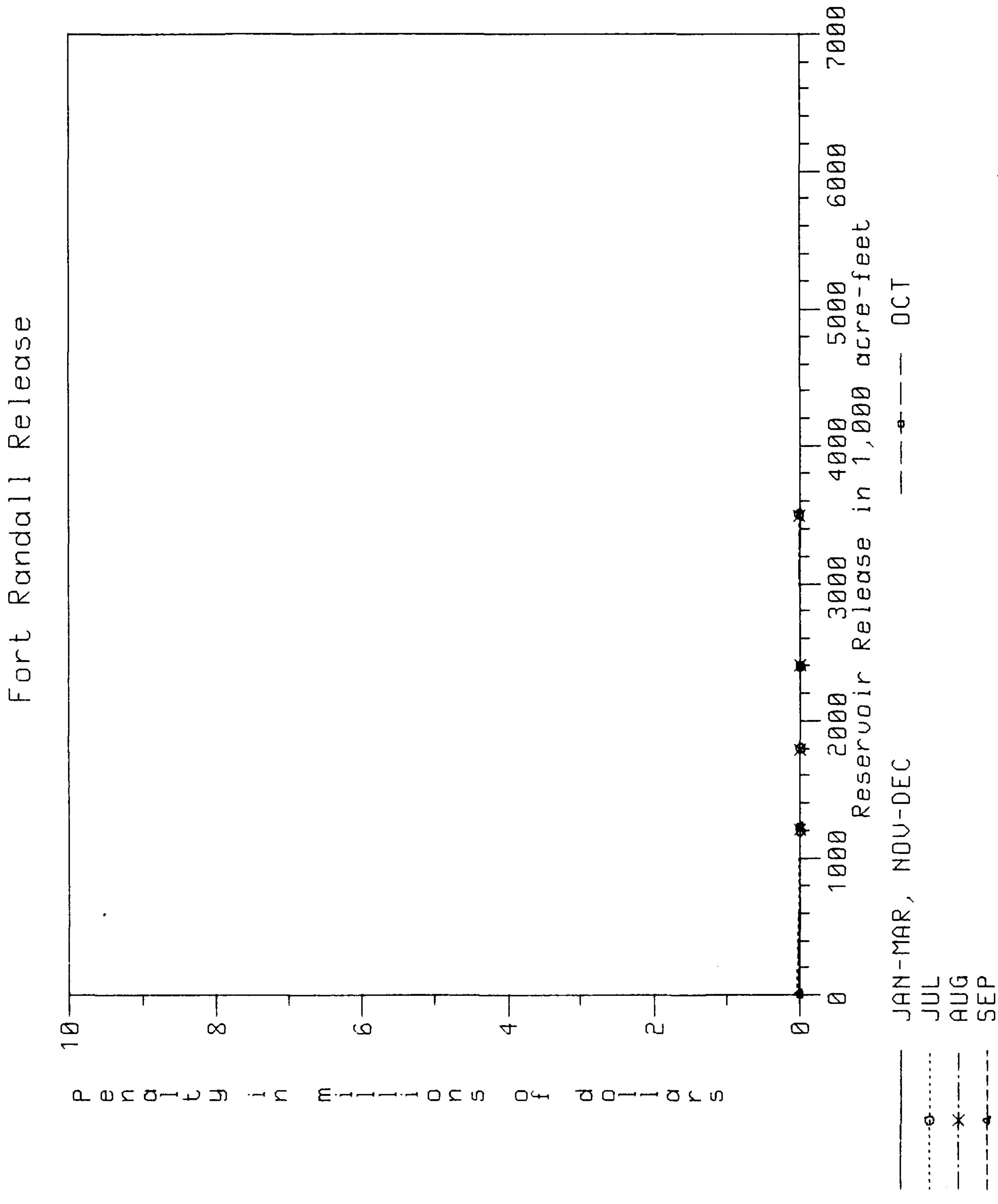


FIGURE E-11 Ft. Randall to Gavins Point (continued)

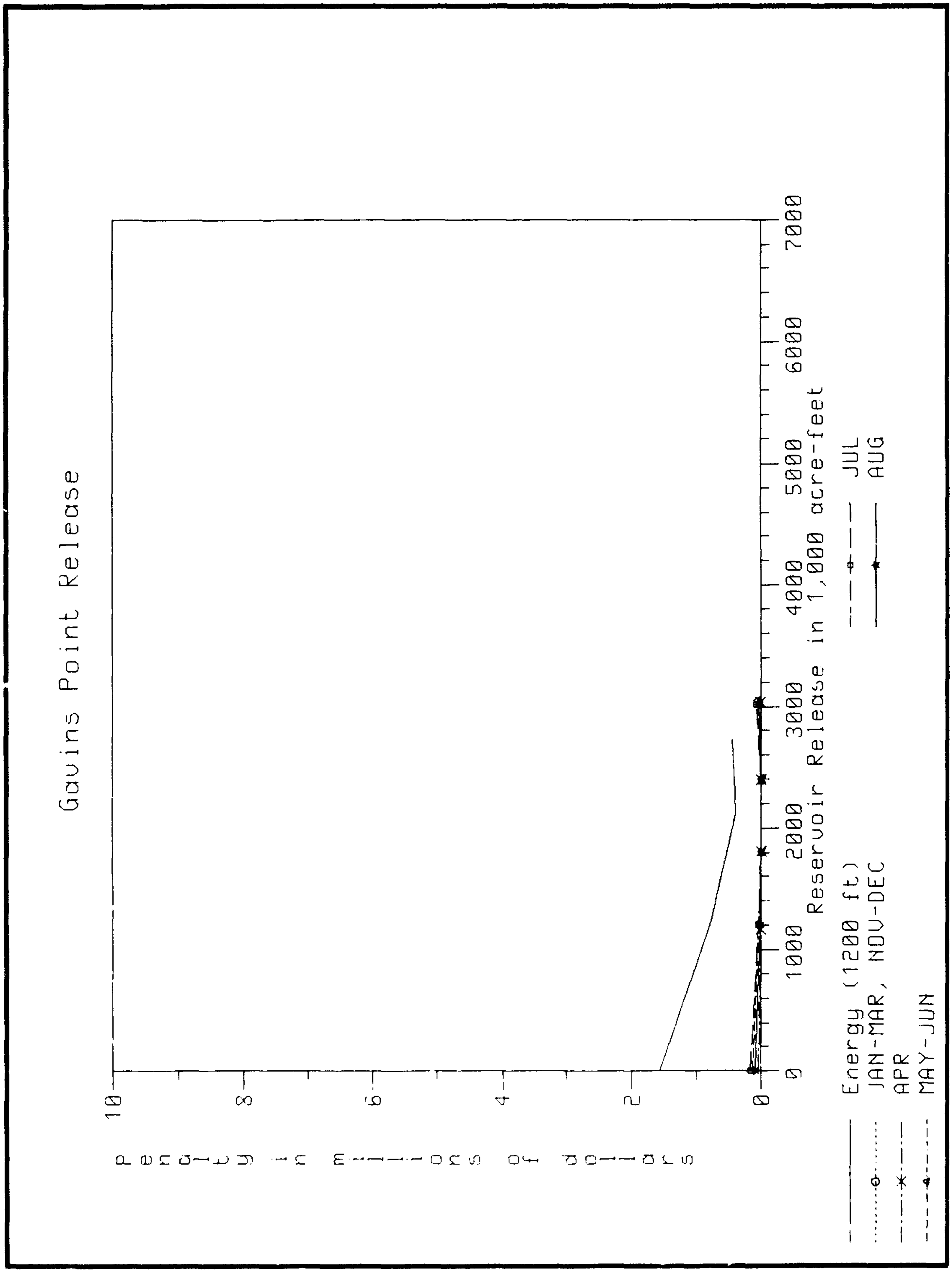


FIGURE E-12 Gavins Point to Sioux City

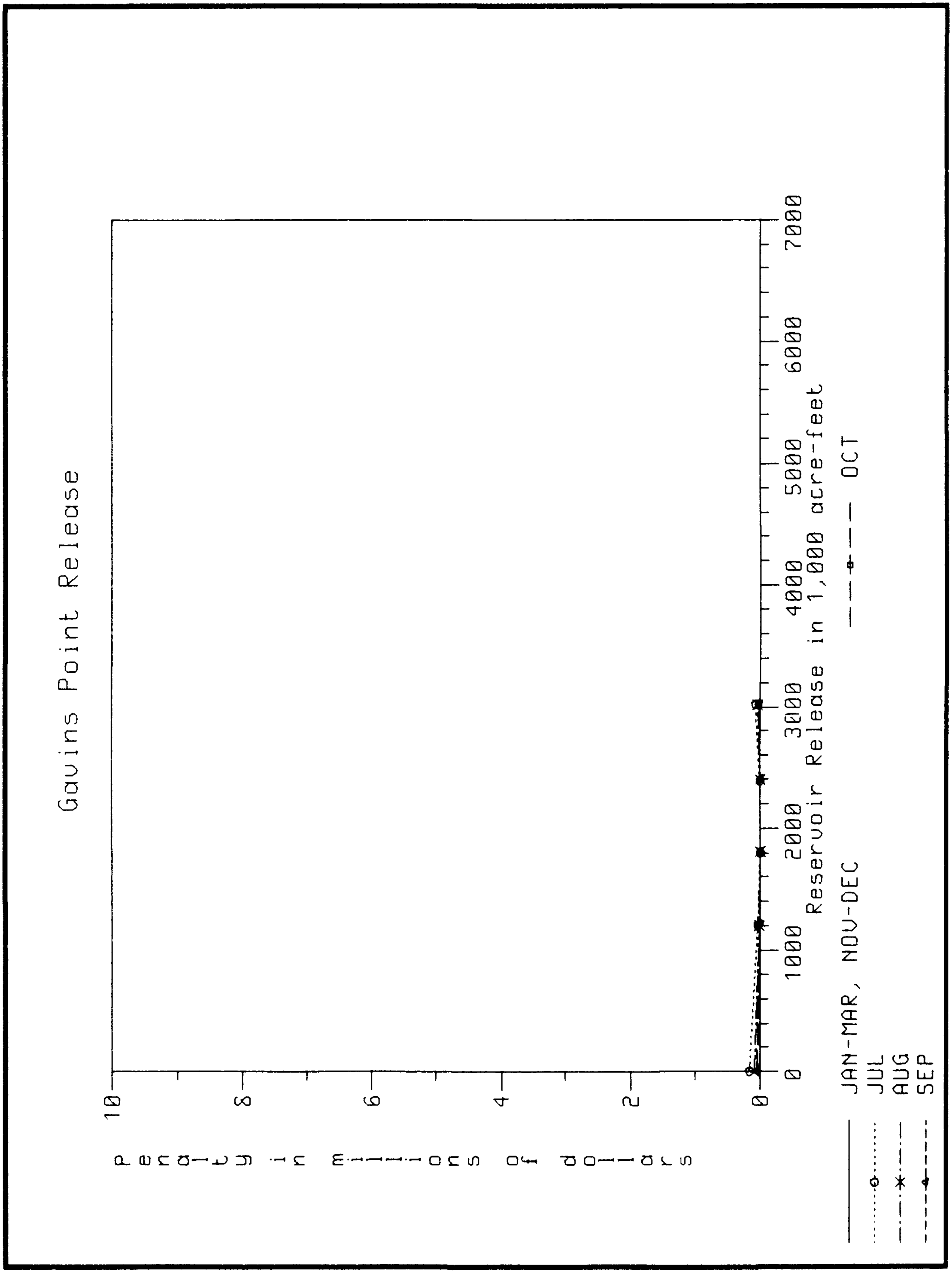


FIGURE E-12 Gavins Point to Sioux City (continued)

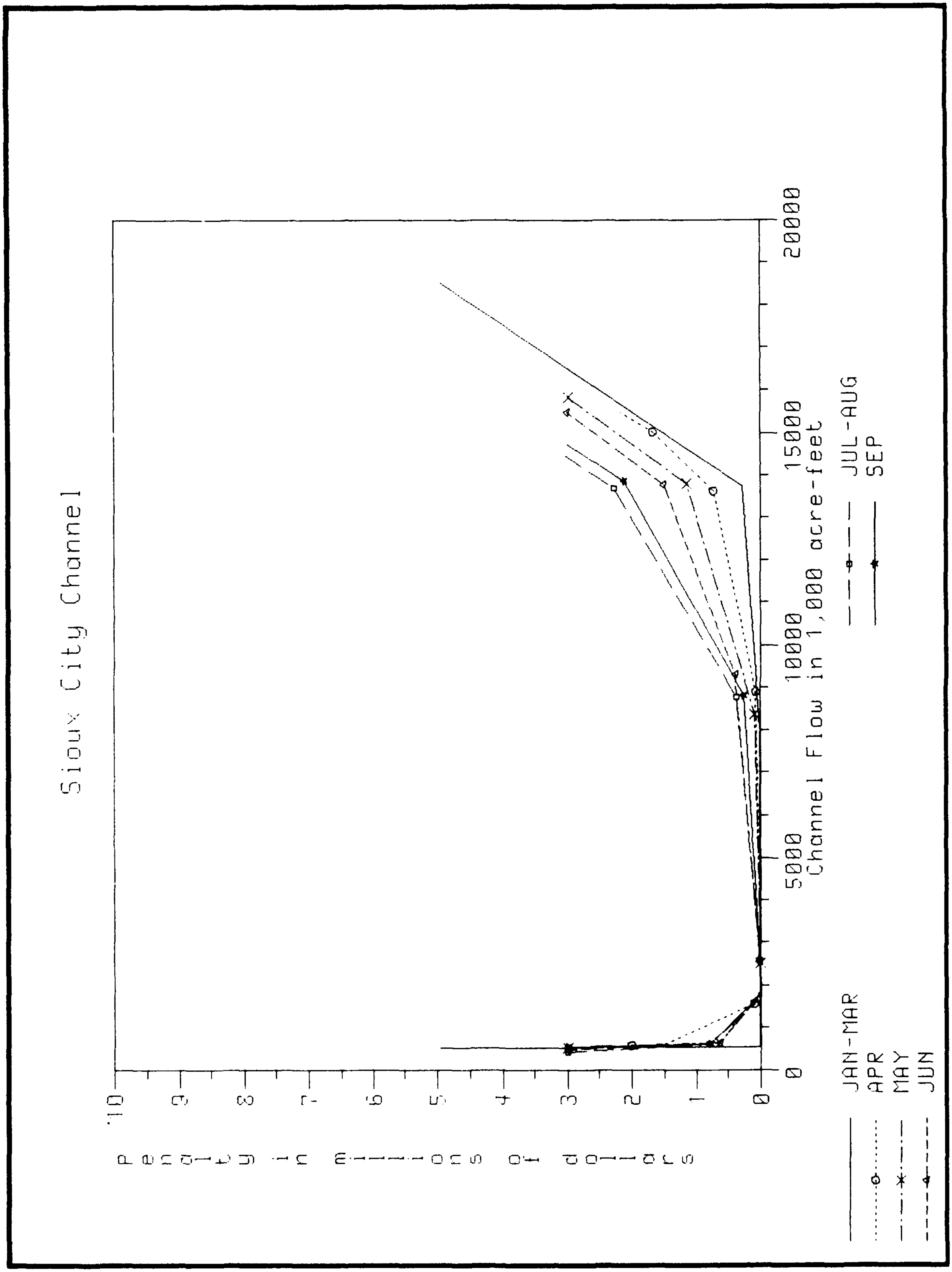


FIGURE E-13 Sioux City to Omaha

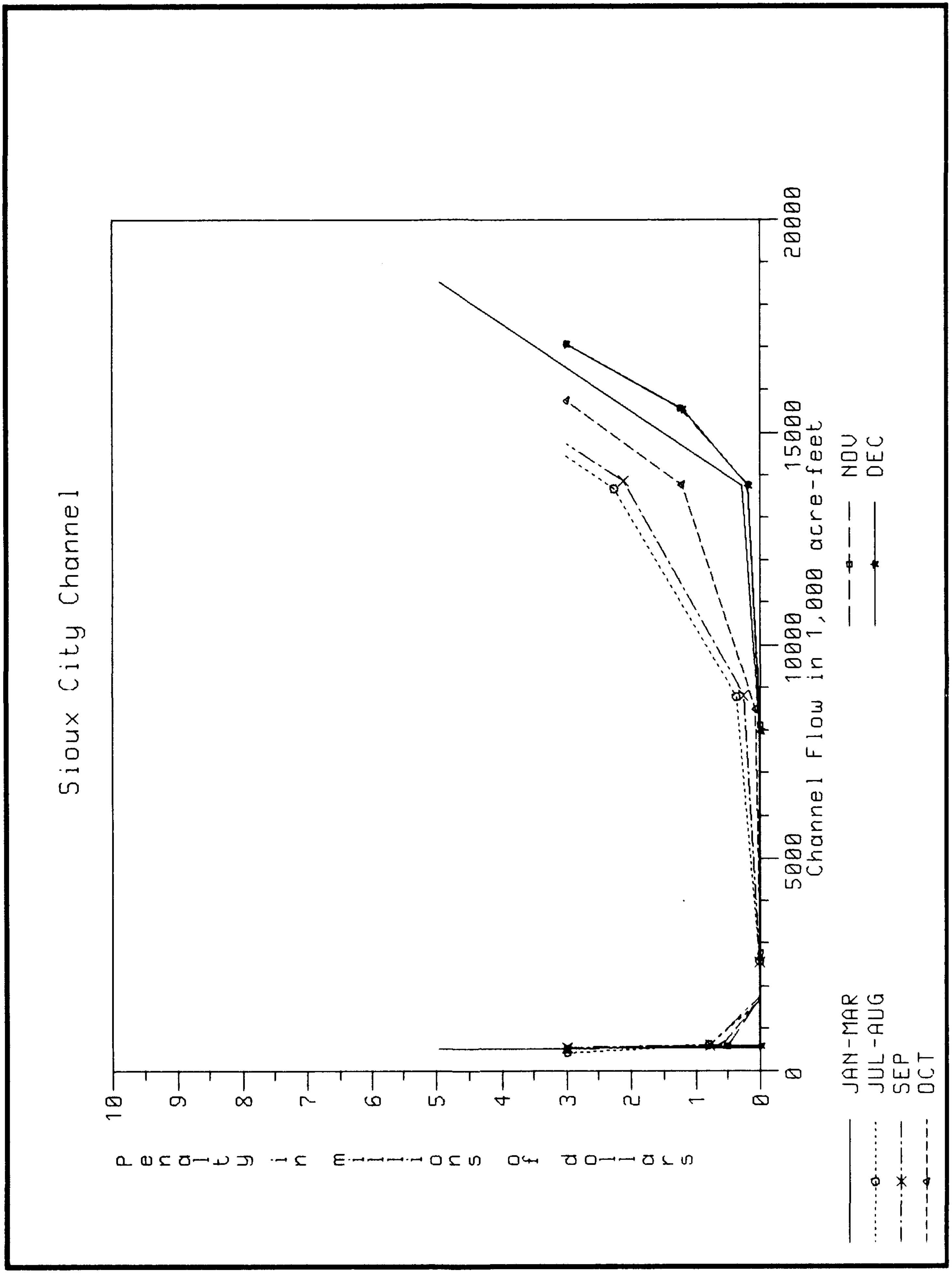


FIGURE E-13 Sioux City to Omaha (continued)

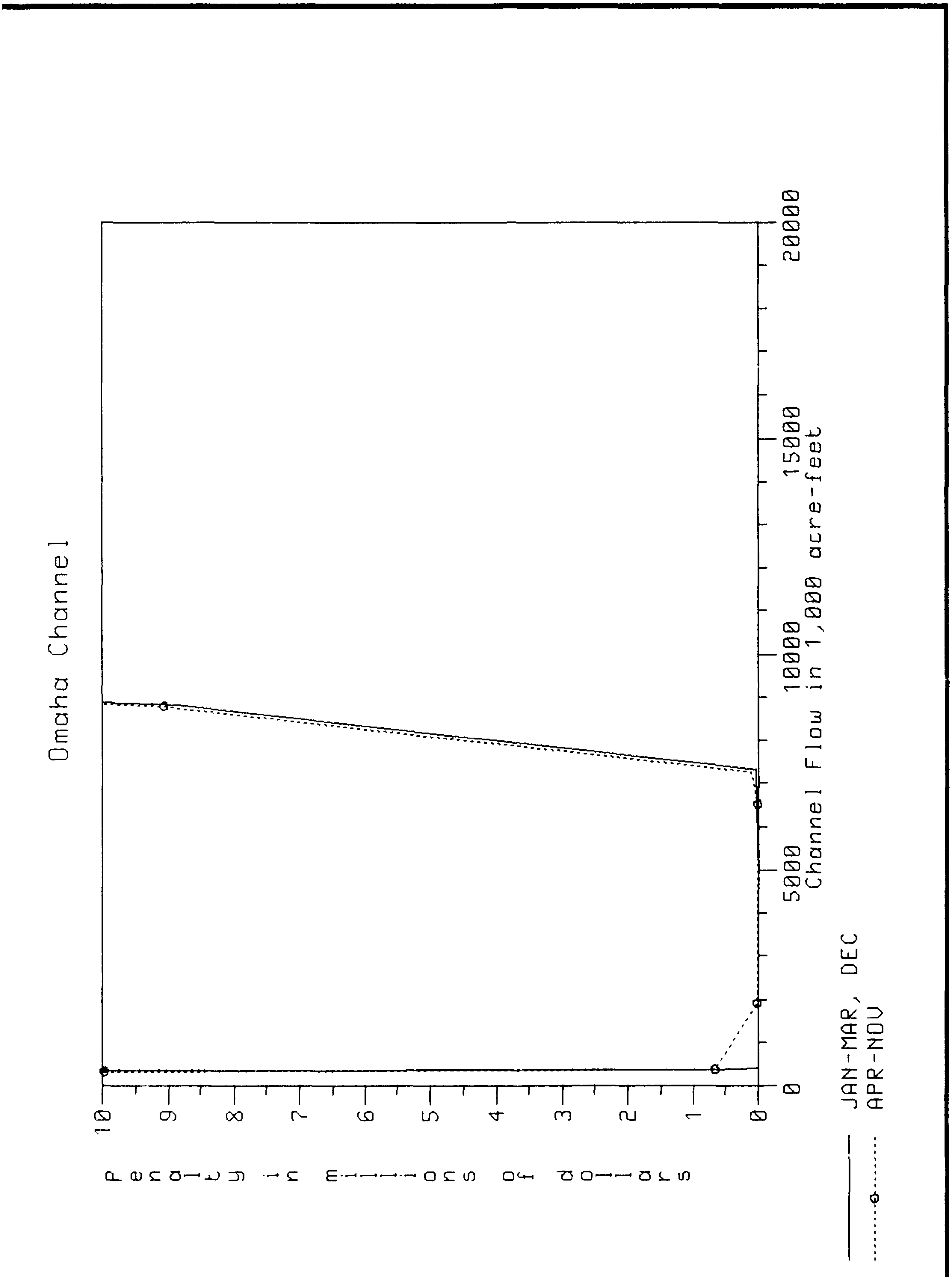


FIGURE E-14 Omaha to Nebraska City

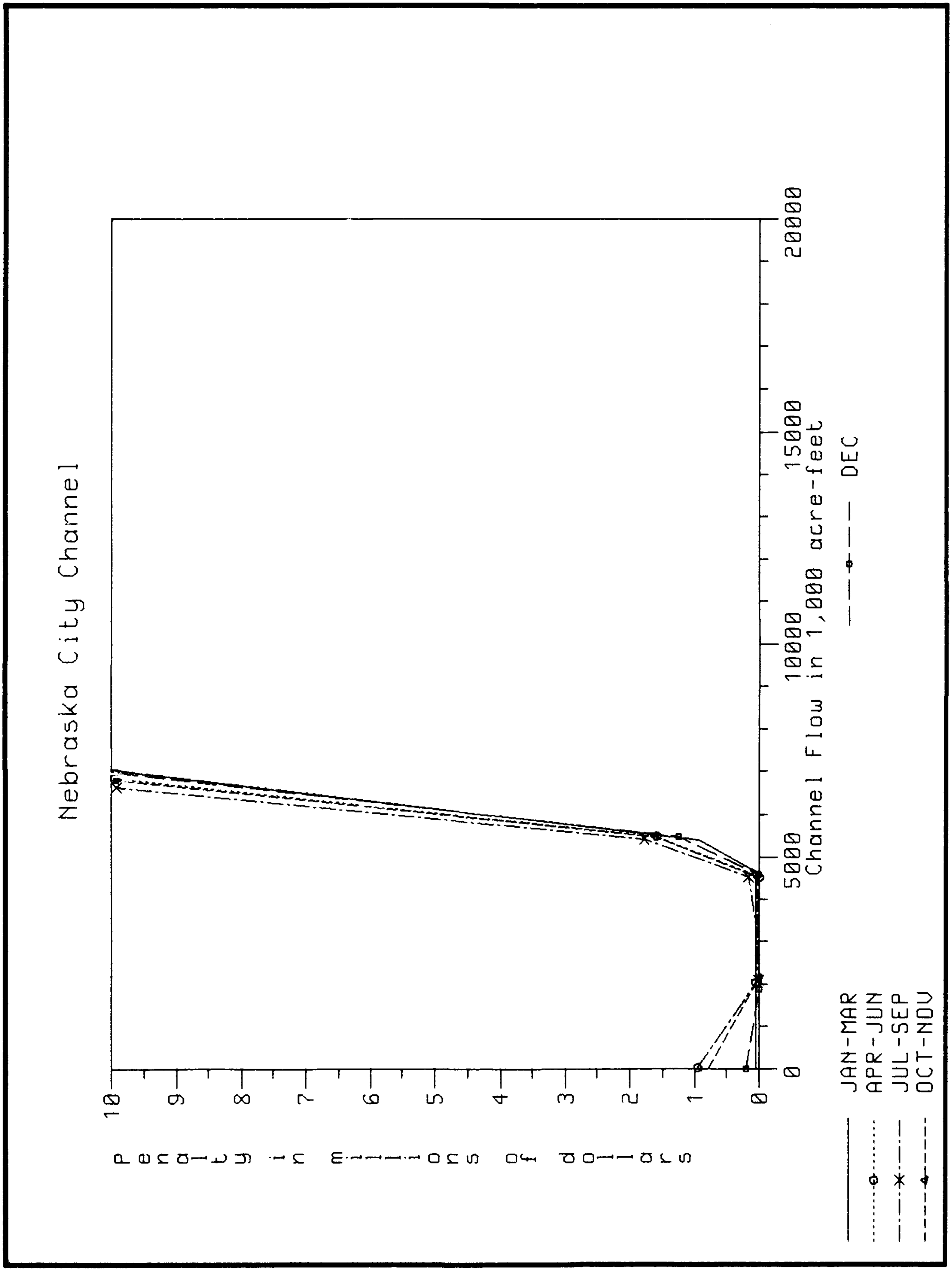
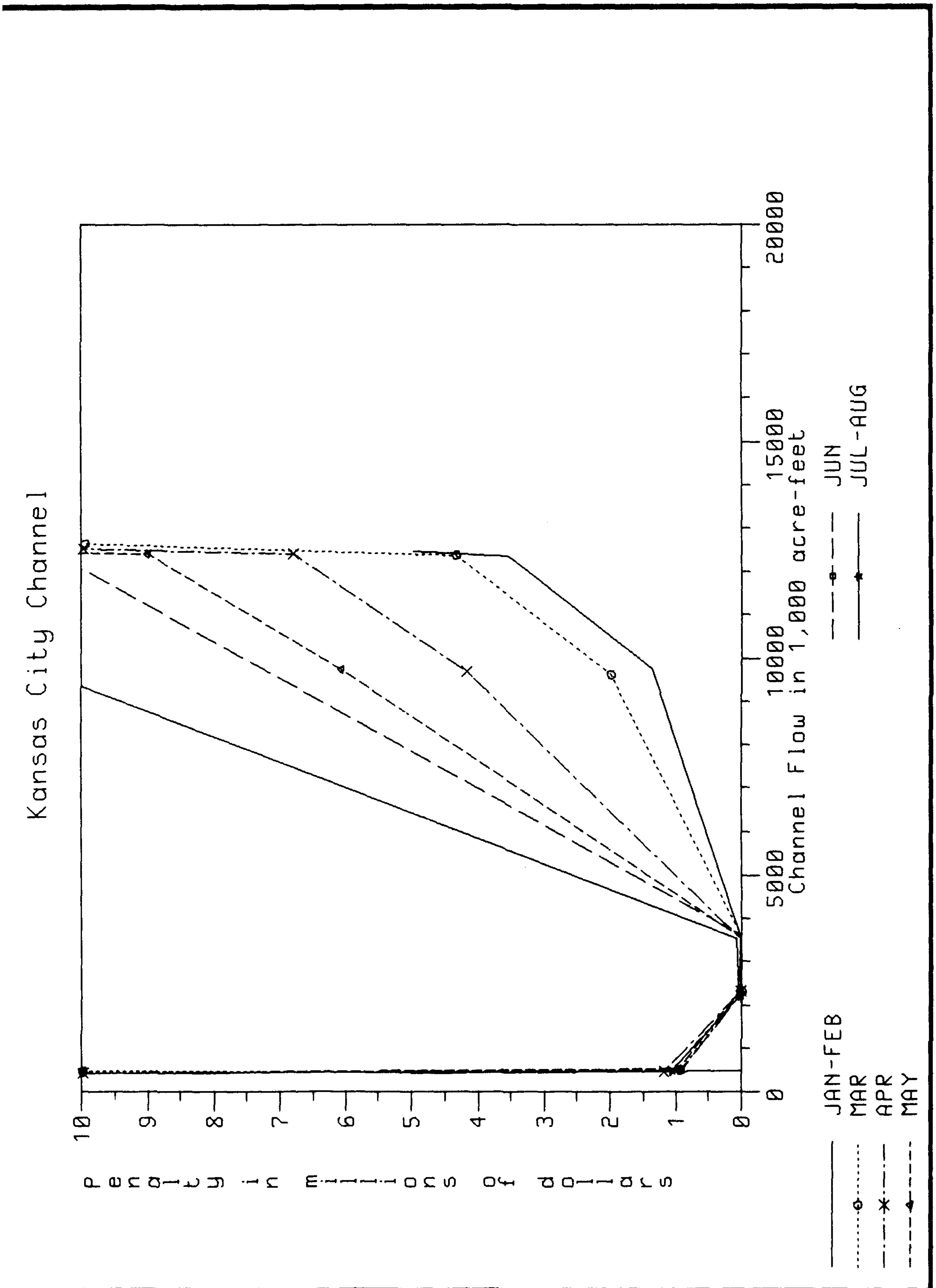


FIGURE E-15 Nebraska City to Kansas City



IGURE E-16 Kansas City to Boonville

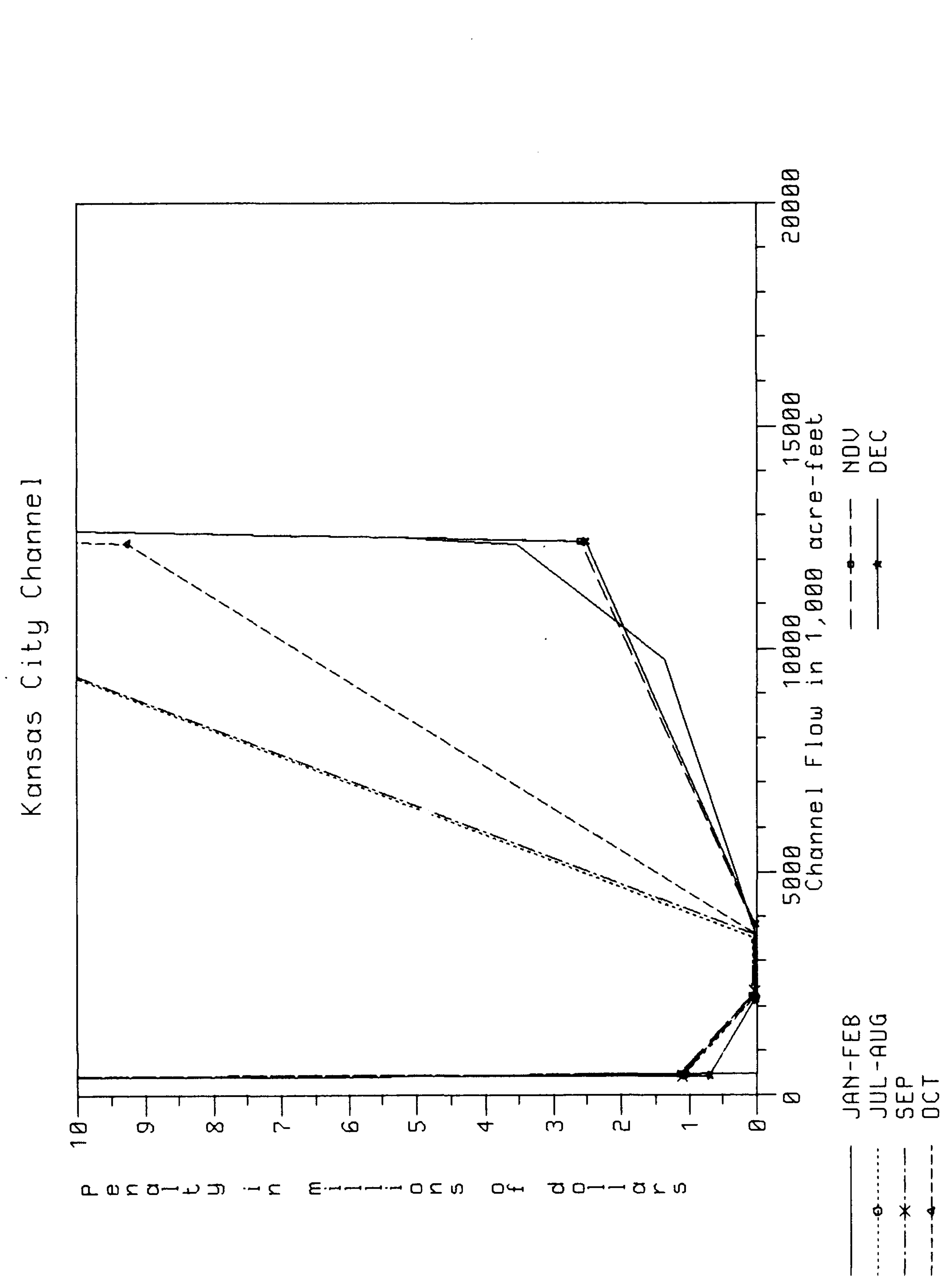


FIGURE E-16 Kansas City to Boonville (continued)

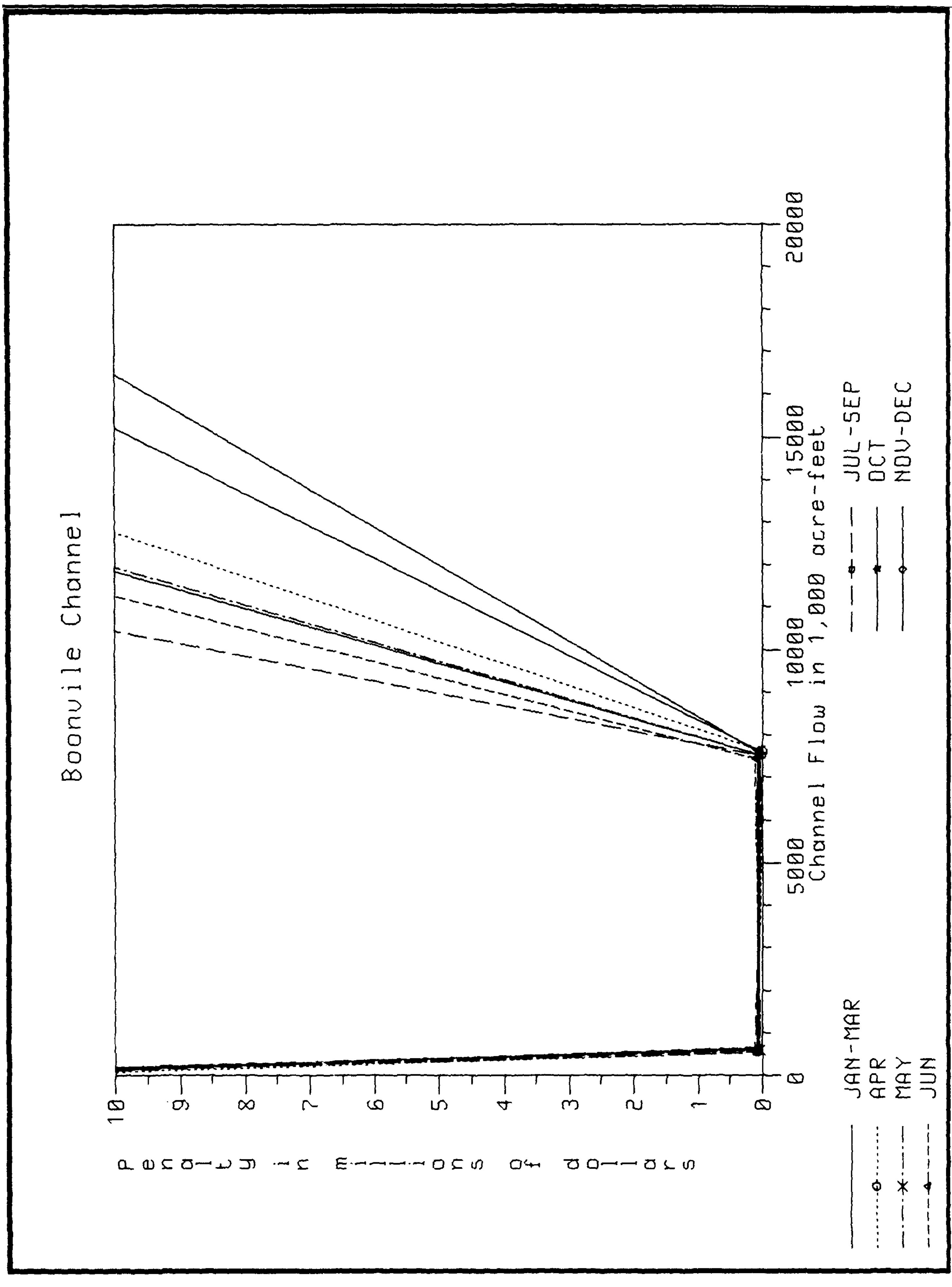


FIGURE E-17 Boonville to Hermann

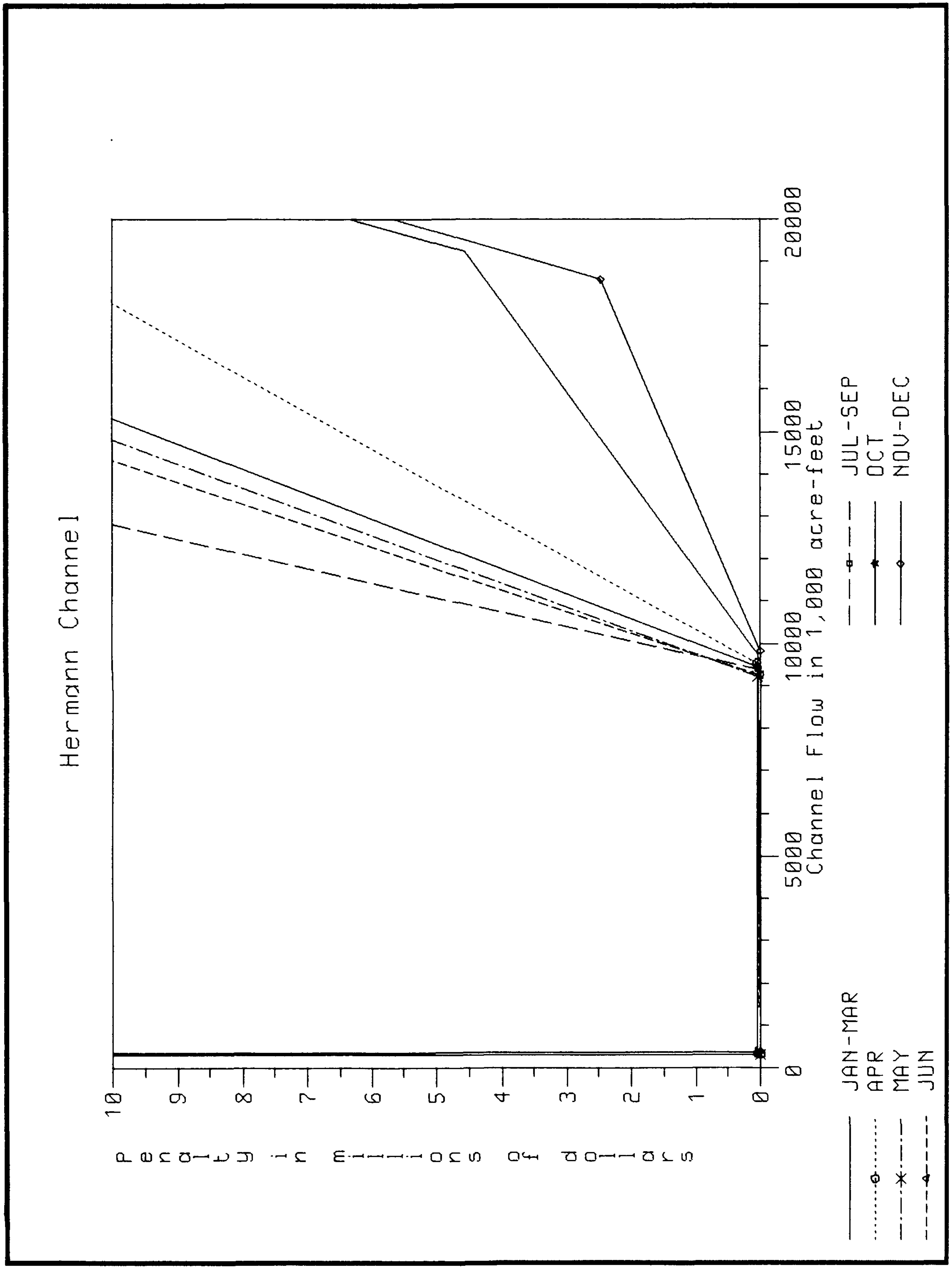


FIGURE E-18 Hermann